ESD-TDR-65-497

Technical Report 406

The Haystack Computer Control System

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27 October 1965

Prepared under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the U.S. Air Force under Contract AF 19(628)-5167.

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

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Group 62

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ABSTRACT

The 120-foot-diameter Haystack antenna operates at X-band and is used for satellite communications, radio astronomy, and radar astronomy. Haystack will be used to study stars, planets, the sun, the moon, and earth satellites. In order to point the antenna to within 1/10 beamwidth (22 seconds of arc) and to provide flexible control and data processing for diverse users, a digital computer has been tightly integrated into the control system. The parameters of an experiment and computer control are arranged via simple operator discourse through a keyboard/printer. The computer system can simultaneously direct the antenna, process receiver signal data, drive convenient operator displays, and permit operator discourse. Thus, processed signal data may be observed in real time, and modifications to the experiment may be rapidly implemented. The computer control system has been completed and is in full operation.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

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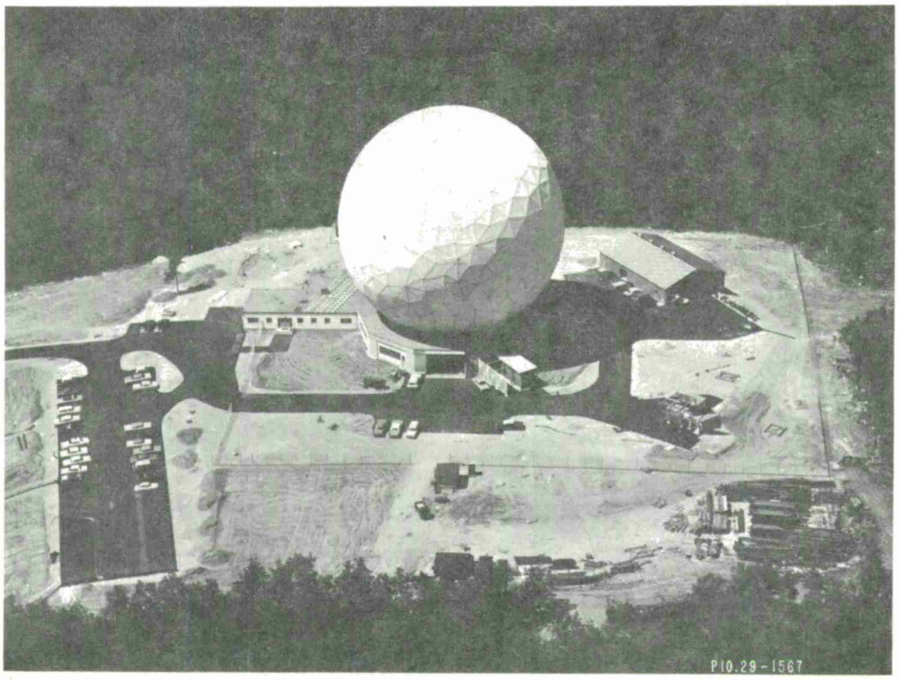

Fig. 1. Aerial view of Haystack Microwave Research Facility.

THE HAYSTACK COMPUTER CONTROL SYSTEM

I. INTRODUCTION

The Haystack Microwave Research Facility in Tyngsboro, Massachusetts, is operated by Lincoln Laboratory as a ground terminal for military communications, radar astronomy, and radio astronomy experiments.[1] An aerial view of the Facility is shown in Fig. 1. The Facility is centered around a 150-foot-diameter rigid space-frame radome (Fig. 2) which contains a steerable 120-foot-diameter parabolic antenna with an X-band (8-Gcps) half-power beamwidth of about 0.06 degree. The half-power beamwidth values at 8, 16, and 32 Gcps are shown in Fig. 3.

For most applications, it is necessary to steer the antenna with a precision on the order of 1/10 beamwidth or 0.006 degree; the system provides this high precision at azimuth and elevation rates up to about 1 degree per second. In addition, the antenna can be slewed at rates to about 3 degrees per second with lower precision. To control the antenna, a sophisticated digital computer system is tightly integrated into the Haystack Facility. While this computer system is primarily intended for "pointing" control of the antenna, it is also used for simultaneous real-time signal processing.

Although computers have been used in numerous instances for antenna control and/or signal processing,[2-6] the Haystack computer control system is unusual in several important respects. First, the very narrow beamwidth and high angular rates required that careful attention be given to each of the components of the control system. Moreover, because the system was designed to be used by many people of varying backgrounds, great flexibility in pointing control was provided, and special attention was paid to the man-machine interface for convenient control of the facility by an operator. Control is obtained by interaction between the operator and the computer through a keyboard/printer, and this interaction employs normal English language and standard mathematical notation. The system permits real-time parameter and control modification by an operator while simultaneously directing the antenna, recording data, processing signals, and providing a multiplicity of display and control functions. The computer system, employing a Univac 490, is a private, integral, and essential part of the Facility. In many other installations, a sizable computer has represented too valuable an asset for primary assignment to real-time control of an antenna facility. The Haystack computer program system involves almost 60,000 locations and represents an unusual investment in computer control capability.

The functional characteristics of the system are described in Sec. II. The equipment configuration and the approach to man-machine communication are described in Secs. III and IV.

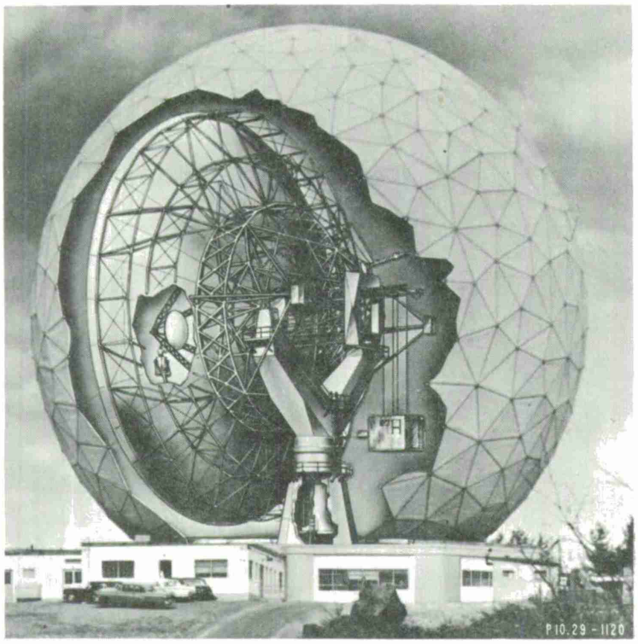

Fig. 2. Placement of antenna within radome.

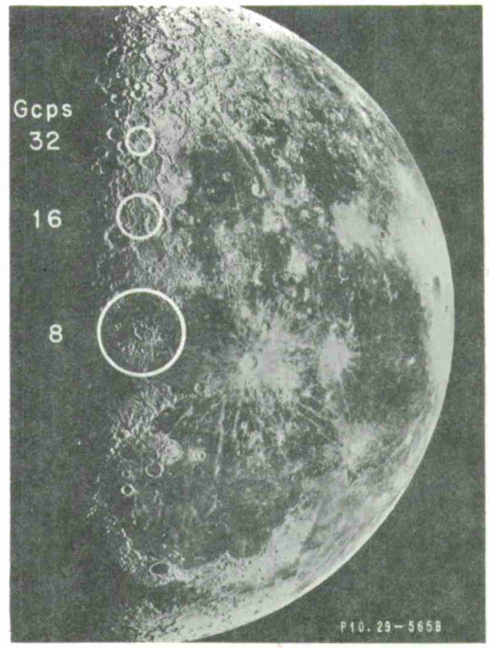

Fig. 3. Half-power beamwidth values at 8, 16, and 32 Gcps.

Finally, the report presents the program organization and a more detailed examination of certain major program sequences.

II. FUNCTIONAL DESCRIPTION

The Haystack system can direct the antenna at earth satellites; at stars, planets, the moon, and the sun; and at specific locations in celestial coordinates or azimuth-elevation coordinates. Around any such chosen point, a wide variety of superposed corrections, excursions, scans, or search patterns may be generated. Such modifications to the basic object position may be used for mapping sections of the sky, studying the lunar surface, mapping the energy distribution of a radio source, acquiring satellites, testing the antenna systems, etc. After such a superposition generates a desired position for the beam at a specific instant of time, additional bias is added to correct for refraction and for any known errors due to structural deformation. The resulting angles are further adjusted to compensate for known deficiencies in the analog servo system. In the case of planets, the angular computations take into account travel-time considerations.

The computer system furnishes the antenna system with estimates of an object's position in azimuth and elevation. Similarly, the computer system furnishes radar receiver systems with computed estimates of range and Doppler. In return, the measured antenna position, range, and Doppler are fed back into the computer. The phrase "pointing system" is used to imply that the primary operating mode involves open-loop computer generation of command angles, and range and Doppler from *a priori* information (such as orbital elements or planetary ephemerides). Measured angles, range, and Doppler are used to "close the loop" within the general-purpose computer only in certain satellite acquisition modes. Measured data are recorded and used by signal-processing programs. When the antenna is being pointed by the computer, the command angles enter a closed-loop digital/analog servo system which produces the actual antenna motion.

A system goal has been to achieve an over-all angular pointing precision of about 1/10 beamwidth, or 22 seconds of arc. In order to contribute as little as possible to this error budget, the computational angular precision has been held to better than one second of arc for stars, planets, the moon, and the sun. In the case of earth satellites, the computational precision is equally good, but the actual output precision is primarily dependent on instantaneous knowledge of orbit parameters (a black art), and the errors are usually much greater. (In order to permit the use of Haystack for tracking earth satellites, an acquisition search pattern technique has been included in the pointing program.)

Although the pointing system is intended primarily for real-time control of the antenna, it is also possible to use the system in a planning mode. The mode is arranged to permit high-speed generation and printing of complete ephemeris data for past or future times or dates. Such a mode is important for studying data previously obtained and for planning the details of future experiments.

The pointing system is normally used with the Haystack 120-foot antenna. However, inter-site coupling links have been installed to connect the Haystack site to two other nearby antenna sites operated by Lincoln Laboratory. This arrangement permits the simultaneous direction of three large antennas at a single target. The coupling links have been so arranged that the parameters of a given pointing experiment may actually be controlled directly via a teletype link into the pointing computer from each of the two remote antenna sites.

Although pointing is a primary task, the Haystack facility, as a whole, is intended to obtain data while pointing. Usually, experimental work requires nontrivial processing of data received during real time in order to obtain useful results. Also, such processing must usually take into account the precise position of the antenna when the data were obtained. Thus, the pointing computer is used also to process incoming signal data in real time, to record such data in conjunction with instantaneous antenna status and position, and to generate computed outputs for operators in real time while the experiment is in progress. The availability of computer-processed signal data in real time is a valuable aid to the experimenter: it permits immediate detection of malfunction as well as experiment modification based on partial results. The computer has been used for data processing in this manner for analysis of radiometric data and data obtained in radar astronomy experiments.

In a system as complex as the Haystack facility, trouble shooting and performance characterization are difficult and important aspects of site operations. Since the computer is available, it may be used for trouble shooting and performance measurements. Programs to measure servo characteristics by means of suitable forcing functions, along with data analysis and recording, have been provided. Also, in normal real-time operation a computer-driven strip chart recorder is used to monitor servo performance.

In case of malfunction, the pointing system also includes a number of alternate backup facilities (including crude analog controls) for directing the antenna. Moreover, the backup controls are integrated to permit simple control of the system by an operator.

III. EQUIPMENT CONFIGURATION

A. General

The Haystack Facility includes many extensive equipment systems. This report considers only the antenna pointing control system and those other subsystems that are intimately related

to the Univac 490 control computer. The focal point for this discussion is the computer and its various connections with the environment. Each subsystem that interacts with the computer is lightly treated; later, additional attention is paid to (1) the primary pointing control mechanization, and (2) the handling of real-time received signal inputs.[7]

Fig. 4. Computer room and control console.

The Univac 490 digital computer was chosen in 1961, and is well suited for complex real-time control operations because of its adequate speed, flexibility, and sophisticated input-output system. It includes fourteen input channels and fourteen output channels. Each channel permits fully buffered block transfers of data with provisions for internal interrupts upon completion of the transfers. External interrupts, which can be generated by the peripheral gear, are also allowed on the standard channels (2 through 13). The primary mode of data transfer control on the in-out channels is via data input or output requests generated by the peripheral equipment. However, the computer has the option of sampling the data on the standard input channels, or of forcing an output on the standard output channels even when there is no request. (Channels 0 and 1 were designed for computer-to-computer communications and are somewhat different in construction and operation. External interrupts are not allowed, and there are no provisions for sampling the input or for forcing an output when there are no external requests.) The machine is equipped with 32,768 registers of 6-μsec cycle time, a 30-bit word length core memory, and a large instruction repertoire. Input and output data are handled in full 30-bit words. More detailed characteristics of this computer are summarized in Appendix A. A view of the computer room with the main antenna control console in the foreground is shown in Fig. 4.

Figure 5 shows a general block diagram of the subsystems connected to the computer, and special attention is paid to the various pieces of equipment that comprise the pointing system. Much of the discussion of the equipment will refer to this diagram.

B. Interconnecting Subsystems

1. Standard Peripheral Gear

The standard Univac peripheral units that are connected to the computer are: (a) a magnetic tape subsystem with four 556-lines-per-inch, 112.5 inches-per-second Uniservo IIIC drives;

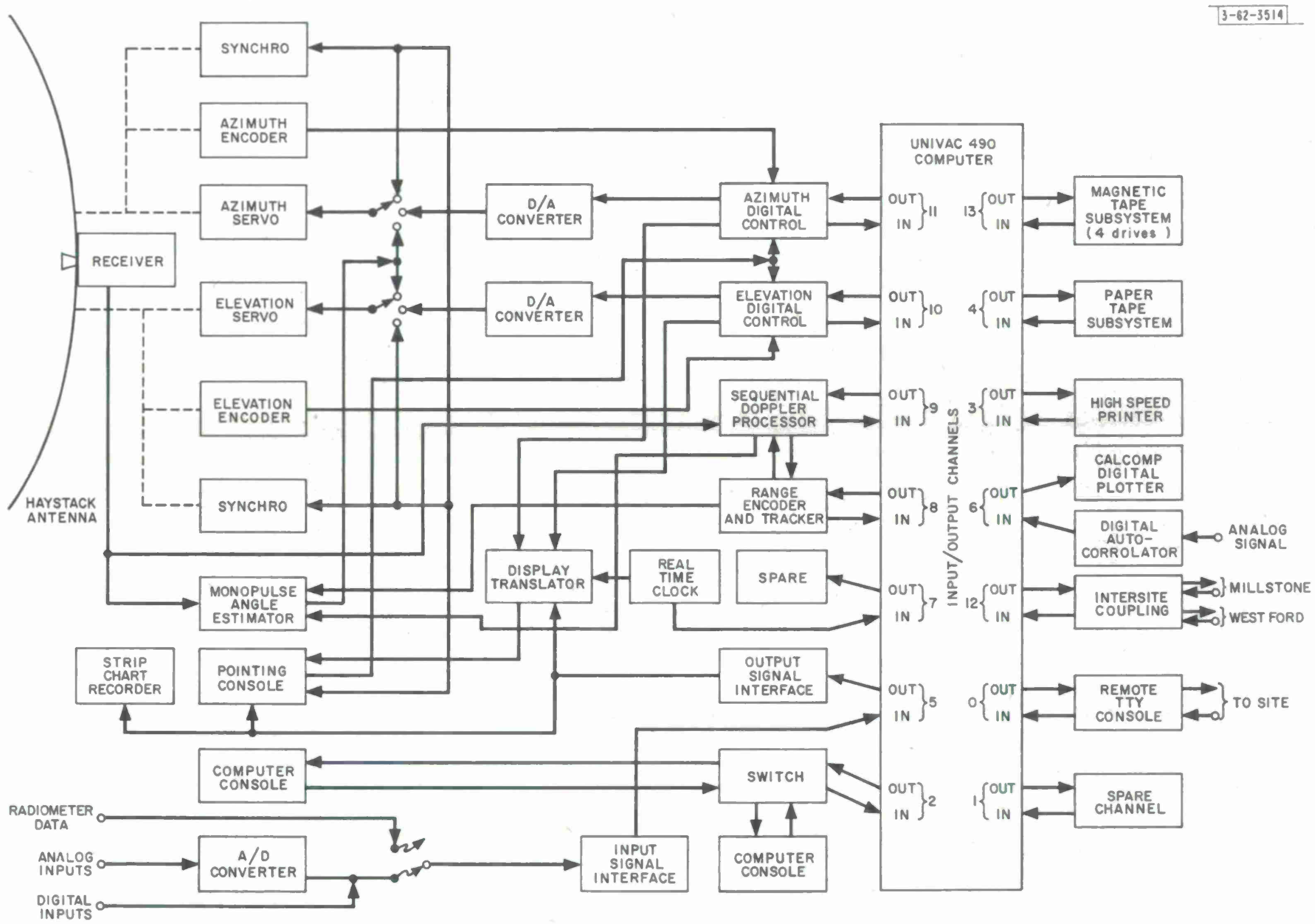

Fig. 5. Antenna pointing system.

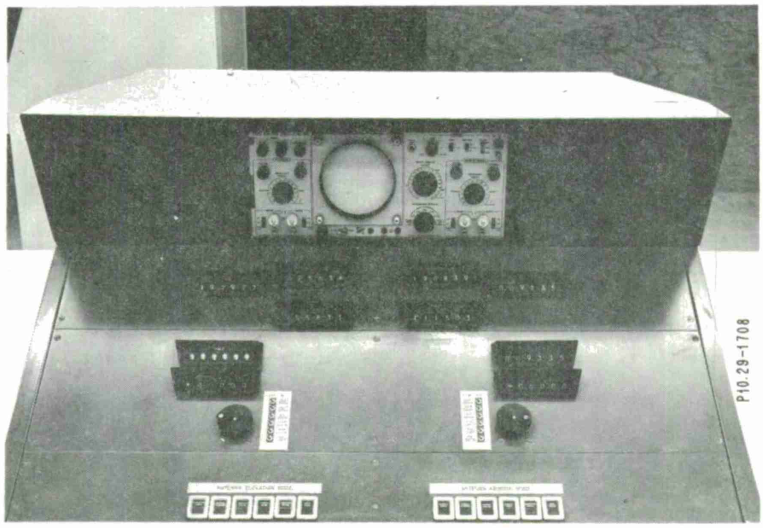

Fig. 6. Control console.

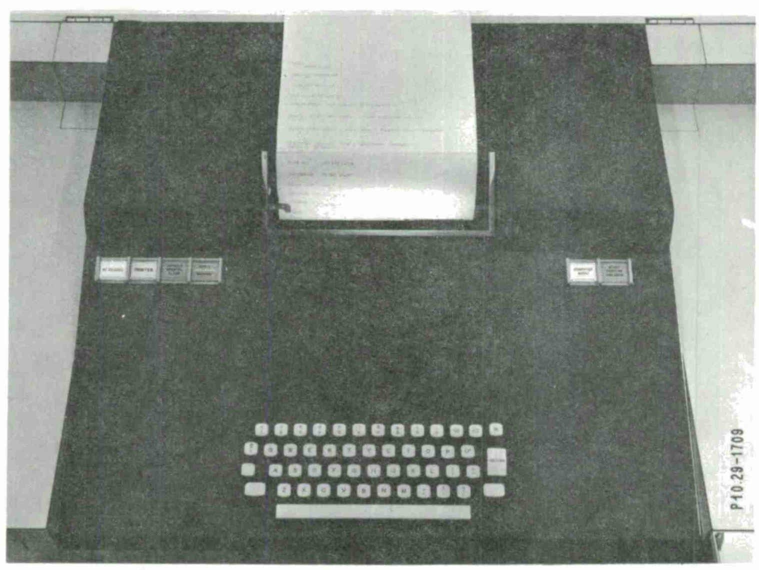

Fig. 7. Keyboard-printer

(b) a paper tape subsystem, including a punch and photoelectric reader; (c) a high-speed (600 lines per minute) line printer subsystem; and (d) two type 8009 control consoles, each of which includes a keyboard and teletype printer. Each subsystem uses both an input and an output channel.*

2. Antenna Pointing

The major units that are associated with antenna pointing are shown as blocks in Fig. 5. These include the pointing console, computer consoles, digital controls, digital-to-analog converters, servos, encoders, synchros, monopulse angle estimator, and display translator. The pointing system is controlled from the pointing console and the computer console, which are located together in the main facility control room. Figures 6 and 7 show close-ups of these consoles. The pointing console contains mode-selection switches, handwheels for manual control, a general-purpose oscilloscope, and Nixie displays of time, antenna command angles, actual antenna position angles, manual bias angles, right ascension (RA), declination (DEC), and local-hour angle (LHA). The displays of RA, DEC, and LHA are driven directly by the computer through the output signal interface, and the other displays are driven by the digital control subsystems and the real-time clock via the display translator.

The control systems for azimuth and elevation axes are independent in operation, and two independent sets of mode switches are included on the console. These switches allow for selecting one of the following modes for each axis: computer digital, manual scan, manual synchro, or autotrack. All normal use of the facility employs the computer digital mode or the autotrack mode; the other modes provide backup and emergency control (or may be used in special situations). When operating in the computer digital mode, the computer generates the pointing angles for the antenna and transfers them to the digital control system at a rate of 250 per second. Manual biases, controlled by console handwheels driving digital incremental encoders, are digitally superimposed upon these computer outputs to produce a digital command angle for the antenna. This command angle is digitally compared with the actual antenna angle, as measured by the encoder for that axis, and a digital error angle is produced. This error angle is converted by the digital-to-analog converter to produce an analog error signal suitable for driving the servo system. This mode of operation is discussed in greater detail in Sec. III-C. The other two digital modes of operation are identical, except for the generation of the command angle. When operating in the manual digital mode, the command angle is entirely controlled by the same console handwheels as those used for bias control in the computer digital mode. When operating in the manual scan mode, the command angle is composed of two components: one is the center of scan angle, which is manually controlled by the console handwheel; the other is an instantaneous scan component, which is generated by special-purpose digital circuitry and is based on manual console selections of amplitude and rate.

The analog modes of control include manual synchro and autotrack.† The manual synchro mode is primarily an emergency backup for the digital pointing system. For each axis, there is a synchro on the antenna mount and a corresponding handwheel-controlled synchro in the pointing console. These units generate an error signal that is fed directly into the servo. The autotrack mode allows the monopulse angle estimator to track a radar target automatically once it

*Further information on these standard units may be found in Univac Technical Bulletins: UT3405, "Univac 490 Uniservo IIIC Magnetic Tape Subsystem"; UT3413, "Univac 490 Paper Tape Subsystem"; and UT2471, "High-Speed Printer Subsystem."

† The autotrack system was not operational as of 1 July 1965.

has been acquired. This system generates azimuth and elevation analog error signals that are used as inputs to the servos. These error signals are also digitalized and made available to the computer on spare input bits in two of the computer input channels.

In all modes, the actual azimuth and elevation angles of the antenna as measured by the encoders are made available to the computer at a 250-cps rate.

As shown in Fig. 5, two computer consoles are connected to the computer through a switch. One of these consoles is located in the computer area near the computer maintenance panel and is employed when the computer is being used for purposes other than for antenna pointing operations. The other console is located next to the pointing console and is used for pointing program control during normal experiments. Only one of these consoles can be active at a time.

3. Intersite Coupling

The intersite coupling subsystem provides a connection between the Univac 490 computer at Haystack and two other nearby antenna sites operated by Lincoln Laboratory (West Ford Communications Site[2,3] and Millstone Hill radar[8]). The link to West Ford transmits azimuth, elevation, Doppler, and range commands to the pointing equipment at that site. These commands are contained in three computer words, and the bits are transmitted in serial over telephone lines at a 2-kcps bit rate, one set of command words being sent every 1/20 of a second. The output to the Millstone link consists of four computer words that contain azimuth, elevation, range, and Doppler commands. These commands are transmitted in serial over telephone lines at a 3-kcps rate, one command set being transmitted every 1/20 of a second. The only return-link computer input from the West Ford site is an external interrupt that indicates a target detection. There are six computer words of return-link computer input from the Millstone radar. These words include: target range, target Doppler, target detection bit, elevation, elevation monopulse error, azimuth, azimuth monopulse error, time, and target-return amplitude from the two receivers. These data are transmitted from Millstone to Haystack in serial over telephone lines at a 10-kcps bit rate. The sets of data words are transmitted at the prf of the Millstone radar (less than 30 cps).

In conjunction with the intersite coupling subsystem, a remote teletype (TTY) console subsystem was built to allow the pointing program to be controlled from either Millstone or West Ford.[9] This subsystem consists of Teletype Model 28 send/receive sets at each of the sites, and control and interface circuitry at the Haystack site. Each such remote teletype acts as a remote "computer console." The inputs to the computer are 5-bit teletype character codes sent from the TTY console keyboards via a telephone line. The outputs from the computer are in the same format and are sent to the TTY console printers via another telephone line. The data transmission rate in either direction is 10 characters per second.

4. Real-Time Clock

The real-time clock is driven by a crystal oscillator (which is phase-locked to the site rubidium vapor frequency standard) and can be synchronized to real time to within 100 microseconds by using a WWV time signal. It produces a binary-coded decimal output that is used by the display translator to drive digital displays of GMT and EST. It also produces a binary output, which is made available to the computer on input channel 7. The binary time is an unsigned 30-bit word with a 100-μsec least significant bit.

5. Sequential Doppler Processor

The sequential Doppler processor (SDP) shown in Fig. 5 is used with a radar having a 2-msec pulse width. This subsystem can automatically Doppler track a target, or it can use computer-predicted Doppler for tracking. For each detectable target return, it generates a measured Doppler value for input to the computer and for Doppler correction in the monopulse angle estimator; it also generates a pulse that is used in the range encoder and tracker for range measurement. The SDP requires a 21-bit binary Doppler command from the computer, and it produces a 21-bit binary measured Doppler value for input to the computer.

6. Range Encoder and Tracker

The range encoder and tracker works in conjunction with the SDP to measure and track the range of a target. This subsystem can automatically range track, or it can use computer-predicted range values. It generates a measured 25-bit binary range value for input to the computer, and it also generates a tracking gate and a false-alarm gate for use in the SDP and the monopulse angle estimator.

7. Output Signal Interface

The output signal interface subsystem is a demultiplexer that produces a 26-bit output data word on any one of six output subchannels. (The highest-order 4 bits of the 30-bit computer output word are used for subchannel selection.) The timing on this channel is determined by the pointing program because the outputs are not requested by the external equipment but are forced out by the program using external function commands. Subchannel 1 is used by the program to generate miscellaneous control or indicator signals for external equipment. Subchannels 2, 3, and 6 carry outputs of right ascension, declination, and local-hour angle. These outputs are used to drive Nixie displays located on the pointing console. Subchannel 4 is used to provide control signals to the radiometer equipment, and subchannel 5 is used to control either a strip-chart recorder or the CRT display on the pointing console. On this subchannel, four 6-bit digital-to-analog converters are used to provide analog signals for four channels of the strip-chart recorder, or two 8-bit digital-to-analog converters are used to provide x- and y-deflection signals for the CRT display.

8. Input Signal Interface

The input signal interface is used to accept signal input data from radar or radiometric receiver subsystems. Such a receiver subsystem may employ a "general-purpose" multiplexer and an analog-to-digital converter that is associated with the interface equipment, or the receiver subsystem may provide parallel digital words directly to the interface. The general-purpose arrangement includes an analog-to-digital converter with 20 addressable analog input channels. This converter generates 15 bits of input data, which include 9 bits, plus a sign bit, for the quantized analog input, and 5 bits to identify the analog channel. The remaining 15 computer input bits can be used for input of digital quantities. Input signal handling is discussed in greater detail in Sec. III-D.

9. Calcomp Digital Plotter

A Calcomp Model 564 digital incremental plotter is connected to the computer on output channel 6. This plotter has a drum which is incrementally rotated to produce x-direction

plotting, and a carriage with a pen which is incrementally positioned to produce y-direction plotting. The pen can also be raised and lowered on command from the computer. The size of the increments in both x- and y-direction is 0.005 inch, and the speed is 18,000 steps per minute. Plots up to $29\frac{1}{2}$ inches wide and 120 feet long can be produced.

10. Digital Autocorrelator

A digital autocorrelator is connected to the computer on input channel 6. This subsystem produces in real time the autocorrelation function of an input signal. The input signal is sampled at a rate up to 10 Mcps; at every 100 msec, one hundred points of the autocorrelation function are transmitted to the computer. The computer can then integrate the data and perform a Fourier transformation to get the power spectrum, which can be displayed on a CRT for use by an operator.

C. Azimuth Control System

The azimuth and elevation control systems are essentially identical in organization and operation, except for the limits of travel. The elevation travel is limited to approximately 92.5 degrees, whereas the azimuth travel is limited by the cable-wrap design to approximately 600 degrees (see Fig. 8, which shows clockwise and counterclockwise overlap zones). For this reason, the azimuth control system is slightly more complex in that, in addition to the angle, a zone must also be defined to specify the position within the 600-degree limit. Figure 9 is a diagram of that portion of the azimuth control system that is used in the computer control mode. This system can be separated into the following major functional parts: the digital command angle generation, the digital antenna angle measuring, and the error signal generation and antenna drive.

The units associated with the pointing command generation are the azimuth interface, the azimuth control generator, and the azimuth buffer translator (Fig. 9). Nineteen-bit pointing angles are obtained from the computer through the interface to the control generator at a rate of 250 angles per second. The format of these angles is binary parts of a circle, with the least significant bit equal to 2.47 seconds of arc. The primary function of the interface is to match the signals of the computer to the control generator, which uses a different type of circuitry.

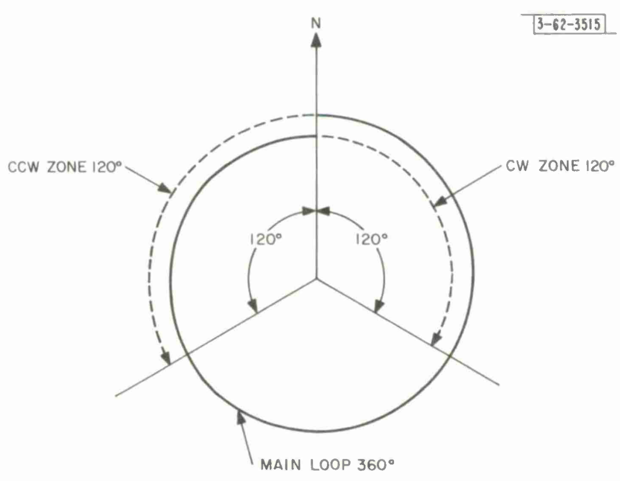

Fig. 8. Azimuth travel zones.

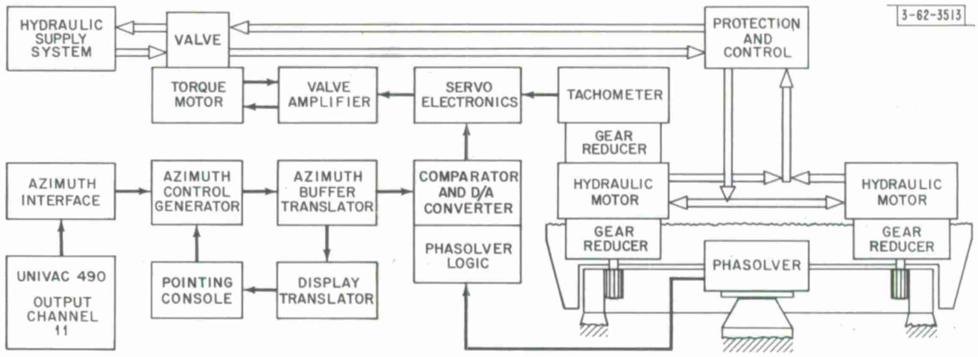

Fig. 9. Azimuth pointing system.

The control generators were constructed by Computer Control Company of Framingham, Massachusetts and use its S-Pac digital logic modules. (These modules are widely used throughout the Haystack digital systems.*) The function of the control generator is to generate the command angle by adding to the computer output the bias that has been selected by the operator at the pointing console. Biases can be added in as little as 2.47 seconds of arc positive, or in negative increments up to ±360 degrees. The resulting command angle is delivered to the buffer translator, which stores this angle for use by the comparator and the display translator.

The actual antenna angle is measured by an unusually precise phasolver encoder system, which was designed and developed for the Haystack program by Telecomputing Corporation, La Mesa, California. The angle phasolver uses two electrostatically coupled, 8-inch-diameter glass discs. One disc is directly coupled to the antenna shaft and rotates with the antenna; the other disc is fixed to the encoder housing and remains stationary. The rotating disc contains three sets of conductive patterns, which are paired sine waves displaced 90 degrees, and the fixed disc contains the exciting and sensing patterns. The phasolver produces electrical phase vector information from which the antenna angle can be determined by the associated quantizing electronics. The output from the electronics is a digital 19-bit angle with a least significant bit corresponding to 2.47 seconds of arc. The encoder system updates the antenna angle at a rate of approximately 305.2 times per second. Included in the azimuth encoder system is the zone-sensing circuitry. This circuitry produces a single bit, which indicates that the antenna is either in the major 360-degree loop or in the clockwise or counterclockwise 120-degree minor loops.

Included in the encoder electronics package are the comparator and the digital-to-analog converter. The comparator has as its inputs the command angle from the buffer translator, the antenna angle from the quantizing electronics, and the zone information; the output is a signed digital error angle. The digital-to-analog converter transforms this digital error angle into a 400-cycle analog error signal for driving the analog servo system. The magnitude of the error is represented by the amplitude, and the direction by the phase as compared with a

*Further information on these modules may be found in Computer Control Company Catalog S-3, "S-Pac Digital Logic Modules."

reference 400-cycle signal. A 9-bit digital error input saturates the digital-to-analog converter and produces the maximum analog error signal. The servo electronics performs phase detection, demodulation, and compensation, and produces a signal input for the valve amplifier. This amplifier drives the torque motor, which is used to control the hydraulic valve in the drive system.

Two 20-hp hydraulic servo drive motors, which have extremely smooth low-speed characteristics, are used to move the antenna in azimuth. These motors are connected to the antenna through gearboxes that have an antibacklash gearing system. A tachometer, which produces a signal used for rate compensation in the servo, is connected to one of the motors.

D. Signal Inputs

The two uses that are being made of the input signal interface (Fig. 5) are the radiometer data input and the planetary radar data input. The radiometer data are fed to the computer via a rather extensive special-purpose digital device, including several multiplexers and an analog-to-digital converter. The planetary radar connection is simpler and uses the general-purpose signal input analog-to-digital converter normally on channel 5 of the computer.

1. Radiometer

Figure 10 is a block diagram of the radiometer data-handling system. The input to the computer from this system is asynchronous with other computer activities and consists of a 30-bit digital word accompanied by an input request signal. The radiometer data-handling system is used only to sample two radiometric receivers for inputs to the computer. However, the radiometer system was designed to permit considerable expansion, as well as rudimentary operations, without the use of the computer. It is thus possible to electronically multiplex 16 analog data sources, to mechanically multiplex 50 analog test points, and to convert from analog to digital.

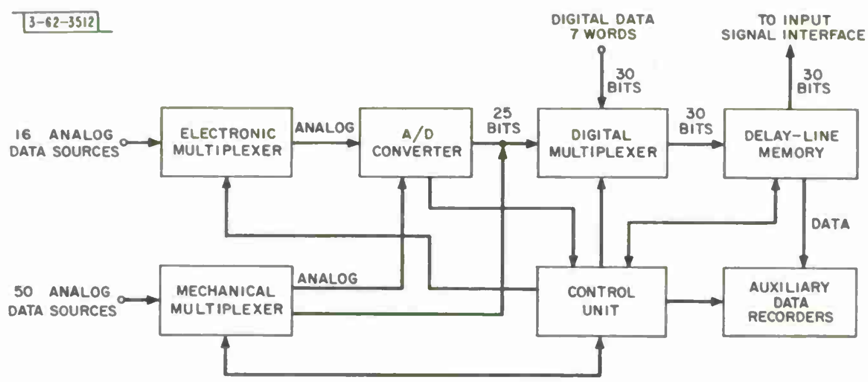

Fig. 10. Radiometer data-handling system.

The digital result may be further multiplexed with seven other 30-bit digital data sources. The delay-line memory is used to store the output words from the digital multiplexer, and any combination of these words can then be transferred to the computer through the input signal interface. The auxiliary data recorders can be used for recording the radiometer data if the computer is not available. The control unit generates the control signals required for proper operation and for sequencing the other units to produce and interlace two types of scans – data scan and auxiliary scan. In the data scan, the 16 analog signals multiplexed by the electronic multiplexer and the 7 digital data sources are included. Each data scan takes 23 milliseconds, and

the interval between scan initiations is adjustable for any length of time between 0.1 second and 100 seconds (which corresponds to radiometer integration time). The auxiliary scan includes the monitor sources multiplexed by the mechanical multiplexer. This scan can be initiated after every 1 to 1000 data scans; the interval is dependent on the data-scan rate and the monitor signals selected.

2. General-Purpose Analog-to-Digital Converter

The planetary radar input uses the analog-to-digital converter that is normally associated with the input signal interface (Fig. 5). The converter is an Adage Voldicon V9AB, which includes a 20-channel multiplexer with sample-and-hold circuits on the first four channels. The four channels, which have the addition of the sample-and-hold circuitry, are used for the planetary radar input channels. For targets such as Mercury, which have a low signal-to-noise ratio, channels 0 and 1 are used. The inputs to these channels are from coherent detectors measuring the sine and cosine components of the radar return signal. The two analog signals from the coherent detectors are sampled simultaneously by the sample-and-hold circuits. The analog-to-digital converter, operating at twice the sample rate, sequentially converts these signals to a 9-bit digital number, plus a sign bit, for input to the computer. In addition to the digitized signal, the input includes a 5-bit channel address that identifies the signal source. The rate at which the channels can be sampled is limited by the maximum conversion rate of the Adage, which is 2500 conversions per second. For radar signals with higher signal-to-noise ratios, channels 2 and 3 may be used for input of the sine and cosine components of the orthogonal polarization signal. In this case, all four signals are sampled simultaneously, and the multiplexer is set to cycle through the first four channels rather than only the first two channels. In this configuration, the converter operates at four times the sample rate.

IV. MAN-MACHINE COMMUNICATION

The Haystack Facility services the needs of a diverse population of users. This population includes users whose training and experience may be in radar techniques, astronomy, communication systems, branches of geophysics, etc. These users may be acquainted with digital computer techniques, but are not normally highly trained in such techniques. Nevertheless, in order to exploit the narrow beamwidth, control of the antenna with a digital computer is almost essential. Therefore, it was quite important to implement control techniques that provided the necessary flexibility without requiring detailed acquaintance with computer techniques on the part of the normal user.

Several alternate approaches are available in a case such as this. One common arrangement is the complete preplanning of an experiment where trained computer experts are used to aid in this planning, and in the preparation of control cards, paper tapes, or other such media in advance of the experiment. This approach has many advantages because it forces an experimenter to consider the entire experiment carefully in advance. However, it has the obvious flaw that it is almost impossible to modify the experiment as a result of data obtained in real time, or in the face of equipment malfunction or any other eventuality. Another approach is the attempted prediction of all possible control modes and the design of enough special-purpose console control buttons, knobs, switches, etc., which are conveniently labeled and which are sampled by the computer to obtain its instantaneous control instructions. This approach breaks down

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TITLE
      RADIOMETER TEST*


GREENWICH MONTH(1-12)
      5*


GREENWICH DAY(1-31)
      19*


2028 IS THE PRESENT GMT


TYPE OF RUN.... REAL TIME (0) OR SIMULATION (1)
     0*


START... AS SOON AS POSSIBLE(0) OR AT A SPECIFIED GMT (1)
     *


BELT(1) SAT(2) AZ-EL(3) SUN(4) STAR(5) PLANET(6) MOON(7) RA-DEC(8)
     5*


NAME(1) OR RA/DEC(2)
      1*


CASSIOPEIA A(0)  CYGNUS A(1)  TAURUS A(2)  VIRGO A(3)
ORION NEBULA(4)  POLARIS(5)
      0*


RIGHT ASC        23H 21M 48.64S


DECLINATION      58D 37' 8.83"


DAY OF YEAR      139


UNIVERSAL TIME 20H 28M 57.00S


OBJECT           CASSIOPEIA A


SYSTEM DATA RECORDING...COMPLETE(0) PARTIAL(1) NONE(2) 0
     0*


DATA PROCESSING PROGRAM..
NONE(0) RADIOMETER(1) RADIOMETER SCAN(2) MERCURY EXP(3)
     1*


 T CAL(1)=50.000 T CAL(2)=50.000 TBASE(1)=10.000 TBASE(2)=10.000


CHANGE CALIBRATION CONSTANTS YES(0) NO(1)
     1*


ANY AUXILIARY LIMIT CHANGES  YES(0) OR NO(1)
     1*
*


SIGN OFF(1) MOD(2) NEXT RUN(3) PRINT(4)
      2*


STAR (1) DATA PROCESSING(2) SCAN(3) RECORDING(4) TIMING(5) OTHER(6)
     3*


SELECT SCAN OR OFFSET
CLEAR(0),HOLD(1),RESUME(2)
AZSCAN(3),ELSCAN(4),AZELBOX(5),AZOFFSET(6),ELOFFSET(7)
RASCAN(8),DECSACN(9),RADECBOX(10),RAOFFSET(11),DECOFFSET(12)
ORBIT- CROSSCAN(13),ALONGSCAN(14),BOX(15),CROSSOFFSET(16),ALONGOFFSET(17)

8*


RA SCAN


PERIOD IN SEC =
                  480*


HALF-ARC IN DEGREES
                        .25*


SCANNING-RESELECT AT WILL
```

Fig. 11. Radiometer test discourse.

in the face of large multiplicities of experiment types and control requirements; furthermore, changes or additions require both new console equipment and program modifications. A third approach, and the one adopted, involves the use of a sophisticated program that can interact with the experimenter through a general-purpose input/output device and that can translate between the language of the user and the requirements of the computer system. All control of the Haystack pointing system is arranged through the use of a standard Univac keyboard/printer combination on which an operator engages in a dialogue with the program system in order to specify his control needs at the moment.

The Univac keyboard/printer (Fig. 7) permits the printing of ten characters per second and includes upper case letters, numerals, and miscellaneous symbols. The keyboard and printer are not tied together; rather, a key strike is read by the computer which, in turn, activates the printer. Normally, the computer prints out the operator responses as well as statements or questions of its own, thus providing a record of the experiment setup.

If such an approach is to work for a wide population of users, considerable care must be exercised in designing the litany. A few of the desirable features are:

(a) The discourse should use ordinary English and standard mathematical notation, which should be unambiguous and succinct.

(b) The units should either be stated or be obvious.

(c) The system should detect format errors or unreasonable numerical values for parameters.

(d) Mistakes should be easy to correct.

(e) The system should provide clear directions to the novice user, but should also permit easy short-cut arrangements for the experienced user.

(f) The facility should be available without interruption at any time and should operate at the user's own speed.

(g) The frequently used control combinations should be easily and quickly handled.

(h) It should be possible to override controls of parameter size for test purposes.

(i) Test and debugging procedures should be provided to simplify modification.

To a considerable extent, the discourse arrangements at the Haystack pointing system provide all the desirable features included in this list.[10] Figures 11 through 13 show examples of operator-machine discourse. On these figures, machine statements and questions normally start at the margin, while operator responses are normally indented. Helpful features that are not shown on the figures include:

(a) Any question may be answered before it has been fully typed. Such an early answer halts the type-out of the question. Similarly, the use of a carriage return (alone) to answer a question tells the machine

```
-62-4282

TITLE
     LES II*

GREENWICH MONTH(1-12)
     5*

GREENWICH DAY(1-31)
     21*

1924 IS THE PRESENT GMT

TYPE DF RUN.... REAL TIME (D) OR SIMULATION (1)
    0*

START... AS SOON AS POSSIBLE(O) DR AT A SPECIFIED GMT (1)
    0*

BELT(1) SAT(2) AZ-EL(3) SUN(4) STAR(5) PLANET(6) MOON(7) RA-DE
    2*

SATELLITE INITIALIZATION

RIGHT ASCENSION OF A/N

 RA0=
    239.771*

 RA1=
    -.57256*

 RA2=
    *

ARGUMENT OF PERIGEE

  W0=
    29 7.899*

  W1=
    .87444*

  W2=
    *

INCLINATION

  I0=
    32.11111*

  I1=
    *

ECCENTRICITY

  E0=
    .3964459*

  E1=
    *

MEAN ANOMALY

  M0=
    -.4121713*

  M1=
    4.647799*

  M2=
    *

EPOCH  YEAR   1965
                *

MONTH(1-12)    5
                *

DATE(0.00-31.999)
                     21.781*

EQUINDX... 1950(0) DR PRESENT DATE(1)   1
                                         *

MODE... TRACK(1) DR JUMP(2)   1
                               *

SYSTEM DATA RECORDING...COMPLETE(D) PARTIAL(1) NONE(2) D
     *

DO YOU WANT ACQUISITION

NO(1)  SEARCH SCAN(2)  LOCAL SCAN(3)
     2*

ENTER SCAN LENGTH IN DEGREES
     2.0*

ENTER SCAN WIDTH IN DEGREES
     .5*

DATA PROCESSING PRDGRAM..
NONE(D) RADIOMETER(1) RADIOMETER SCAN(2) MERCURY EXP(3)
    0*
*

SIGN OFF(1) MOD(2) NEXT RUN(3) PRINT(4)
     4*

TAPE IS OK(D) REWIND IT(1) END FILE+REWIND(2)
     2*

ELECT O/P... HSP (D)  BCD TAPE (1)  BOTH (2)
     2*

SET TOP OF PAGE AND CLEAR PRINTER CHANNEL.

TITLE FOLLOWS

LES II

GMT START (HHMMSS)
     *

GMT END (HHMMSS)
     *

FOR EVERY N TH DATUM ENTER N (0-500)
     100*
```

Fig. 12. Satellite acquisition discourse.

```
SIGN OFF(1) MOD(2) NEXT RUN(3) PRINT(4)                    -62-4283
     3*
TITLE
     DEMO2*
1643 IS THE PRESENT GMT
NORMAL START (Y OR N)
     Y*
BELT(1)  SAT(2)  AZ-EL(3)  SUN(4)  STAR(5)  PLANET(6)  MOON(7)
     6*
MERCURY(1)  VENUS(2)  MARS(4)  JUPITER(5)  SATURN(6)  URANUS(7)  NE(8)

     2*
JULIAN DAY      2438600
RIGHT ASC       5H 30M 27.99S
DECLINATION     18D 1' 6.66"
DAY OF YEAR     205
UNIVERSAL TIME  16H 43M 18.00S
DISTANCE   A U  0.4299164
PLANET          VENUS
```

Fig. 13. Planet discourse.

to use a standard answer (usually, the last answer stated for that question). These two abbreviated answering techniques permit a rapid setup for an experienced user.

(b) The "attention" of the discourse system may be obtained at any time by an operator striking an "attention symbol," no matter what the machine may be doing and without interfering with whatever the machine may be doing. Thus, dialogue can be carried on with the intent of modifying experiment parameters, even while the pointing system is proceeding to direct the antenna as previously specified. When the new parameter has been specified, the system simply adjusts and uses the new parameter.

(c) Some discourse subsets essentially "stay with the operator" (on the assumption that further instructions will soon be forthcoming) and do not require use of the attention procedure. For example, if one is scanning the antenna, new scan commands can be entered immediately.

(d) Much consideration has been given to uniformity in the design of questions, the ordering of positive and negative answers, the standard use of conventions (such as carriage returns), and the layout of multiple-choice questions.

This type of computer control represented a sizable departure in thinking for many of the potential users of the system. Nevertheless, numerous users have employed the system with considerable satisfaction, and the over-all reaction has been positive. As the system has been used, it has become clear that certain discourse subsets were less convenient than others, and such imperfections have been rectified whenever possible. It appears that the user's reaction to such a system is highly dependent on the small details of convenience and flexibility. (A similar conclusion has been reached by many workers studying time-shared systems. For example, a major conclusion of the JOSS[11] effort relates to the importance of convenience. Of course, the design of convenient techniques for discourse in the limited field of antenna control is somewhat simpler than the design of convenient discourse for a more generally oriented man-machine relationship.)

Care was also taken to permit easy use of the computer from a cold start. After power is turned on, it is only necessary to mount two magnetic tapes and depress one button labeled

"start pointing program." This results in proper machine clearing and a complex (but automatic) "bootstrap" procedure that deposits the necessary programs in core storage and starts the system.

V. ORGANIZATION OF REAL-TIME PROGRAM

The pointing program is normally available for use on one of the computer's four magnetic tape drives. A second drive holds tabular ephemeris data for solar system and celestial targets, and the two remaining drives are used for recording blanks. Initial loading of the program tape places most of the pointing program in core storage at the outset. The operator then engages in the preliminary discourse necessary to specify an object class (e.g., planet). Based on this specification, the proper additional "plug-in" packages of program and tabular data are transferred from tape to core. The program now operates without any further tape transfers, except for output data recording.[12]

The program computes new points for the antenna in 2-second increments of time called frames. During each frame, azimuth and elevation tables are transmitted to the servo system via buffered block transfers under control of external timing. By using a straightforward alternating buffer technique, the program is computing new tables for the next frame, while the current frame's data are going to the antenna servo. The azimuth and elevation tables provide 250 points per second (500 points per frame) in order to ensure smooth antenna motion. This large number of data points is obtained by employing 4-point interpolation to obtain 250 points per second based on main computations of new points every 2 seconds. This technique requires that the system computations lead actual real time by several seconds in order to use a standard 4-point interpolation technique. Figure 14 shows this timing arrangement. On this figure, the numbered points depict 2-second main-frame time boundaries. The intervals A, B, and C illustrate the time spent in each frame by the main routine, which computes new points for the

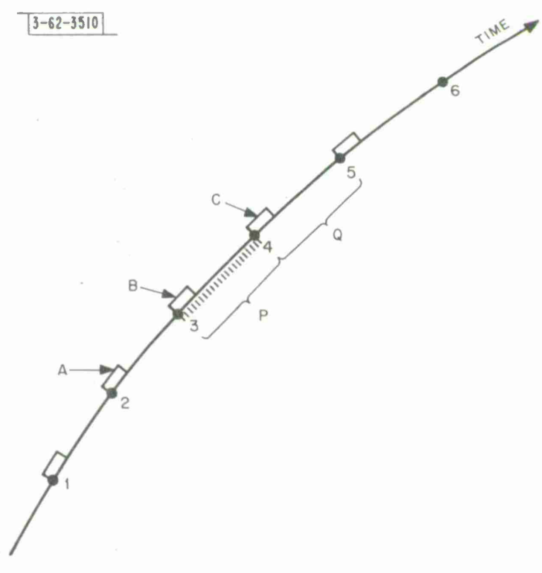

Fig. 14. Frame timing.

antenna. Thus, during period A, it is necessary to compute the 500 points labeled P, which will be needed during the succeeding 2-second interval. In order to do this, the computations proceeding during period A must have available the main computed points for times 2, 3, 4, and 5 (the required points for 4-point interpolation over the period P). Thus, during time period A, the program system first computes a new point (point 5) and then, by using the previously

available points 2, 3, and 4, the program computes the 500 points for the interval P. Similarly, during interval B, the program determines new main point 6, and then computes the required interpolated points to be used during interval Q. When the system is being started, special arrangements must be made to compute several points ahead in order to obtain four main points surrounding the required interval at start-up time.

Determining new main points is done in an interrupt routine, initiated every 2 seconds by an internal interrupt, which is generated when a 500-word azimuth buffer table is emptied by the in-out system. The external timing, which controls the transfer of data from this buffer table to the antenna servo, is tightly locked to the facility master clock so that the buffer table is emptied at precisely the correct times for the transmission of particular words to the servo system. The last word in the table is taken, and the interrupt is generated at precisely the 2-second time. Thus, the in-out timing is a convenient way to lock the internal program timing to real time. The arrival of accurately timed pulses to activate the input-output channels is adequate to keep the program in step with real time, but a method is also required to provide an absolute time reference. This is handled by program-controlled reading of a digital time register (driven by the facility master clock) when the system is started and at periodic intervals thereafter.

A. Main Pointing Computation

Once the 2-second interrupt has occurred, control is transferred to the main pointing computation routine. This routine has, as its goal, the generation of one new azimuth, elevation, range, and Doppler data point for the proper future time (6 seconds ahead) and the subsequent generation of 500 interpolated points for the forthcoming 2-second interval. Previous discourse with the operator will have selected any one of the available celestial computation programs and one of these programs would operate. These programs are:[13-19] (1) West Ford belt, (2) satellite, (3) fixed azimuth and elevation, (4) sun, (5) star, (6) planet, (7) moon, and (8) fixed right ascension and declination. Except for fixed azimuth and elevation, these programs provide as their output the distance ρ, the right ascension α, and declination δ of the required point along with the derivatives $\dot{\rho}$, $\dot{\alpha} \cos \delta$, and $\dot{\delta}$. In the case of fixed azimuth and elevation, operator-chosen values of azimuth and elevation are provided directly, and a flag is left to omit a normally following coordinate conversion. These celestial point computations are handled in three distinct ways as a function of object class: in the case of the sun, the moon, and planets, the program starts with tabulated data at hourly or daily intervals, based on magnetic tapes furnished by the Naval Observatory.[20] Interpolation in these tabulated data, with appropriate correcting terms, gives rise to points at the "2-second" required time. In the case of stars, prestored (common radio sources) or operator-entered, values of right ascension, declination, and epoch are properly updated to the required "2-second" time by using enough terms to obtain an accuracy of better than 1 second of arc. For satellites or belts, operator-entered orbital elements are updated in real time by taking into account perturbations due to the second harmonic of the earth's gravitational field. Such updatings are used directly in the necessary equations to obtain the celestial coordinates at the required 2-second point.

After computation of a geometric point in celestial coordinates, the following additional steps occur (Fig. 15).

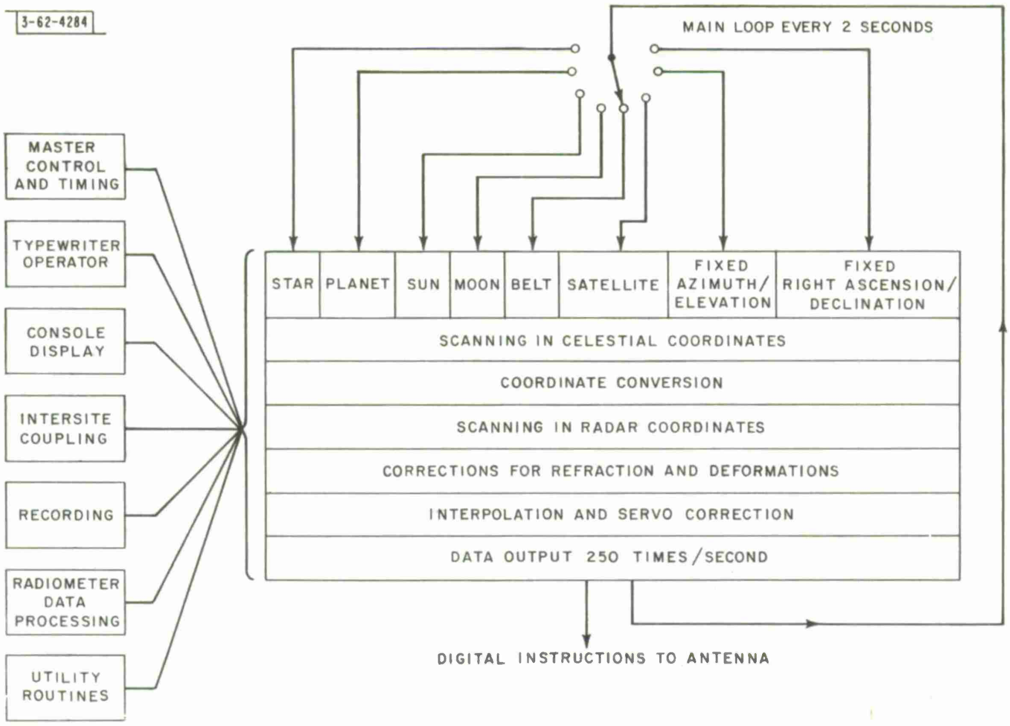

Fig. 15. Pointing program outline.

1. Celestial Scan

Depending on operator parameters, the celestial scan program[21] can:

(a) Scan in right ascension, in declination, or in both simultaneously,
(b) Trace out a raster scan within a box oriented in right ascension or in declination,
(c) Provide any fixed offset in right ascension, in declination, or in both.

2. Coordinate Conversion

The coordinate conversion program[22] takes ρ, α, and δ (as modified by celestial scan) and computes the corresponding radar coordinates; range R; azimuth A; and elevation E. Using, in addition, $\dot{\rho}$, $\dot{\alpha}\cos\delta$, and $\dot{\delta}$, it computes the range rate $\dot{R}$.

3. Radar Scan

Depending on operator parameters, the radar scan program[21] can:

(a) Scan in azimuth, in elevation, or in both simultaneously,
(b) Trace out a raster scan in a box oriented in azimuth or in elevation,
(c) Scan (over a short arc) along or across the orbit of a satellite or belt,
(d) Raster scan in a box oriented along the orbit,
(e) Provide any fixed offsets in azimuth or in elevation, or along or across an orbit.

4. Correction

To account for atmospheric refraction and for structural departures of the antenna from the ideal, a correction program[23] adds in the appropriate bias to azimuth and elevation so that the electrical axis of the beam will be directed at the desired point.

5. Interpolation

Having retained the last three points (in radar coordinates) and having just obtained a new point, the interpolation program[24] is set to fill up the 500-point azimuth, elevation, and Doppler buffers that will be valid for the next 2-second frame. In this interpolation process, compensation terms may be used to improve the performance of the servo system. Range is computed for the middle of the frame, and Doppler is computed from the range rate.

6. Intersite Coupling

In addition to the foregoing steps, which are directed at providing points for Haystack, other programs in this main pointing routine properly fill output buffers with appropriate subsets of the computed interpolated points for transmission to the nearby 60-foot West Ford antenna site and to the nearby 85-foot Millstone Hill antenna site.[15]

B. Intercom

The pointing program system[12] can be considered as having three major logical control paths (Fig. 16). The first path is an infinite-length loop that may be freely interrupted. This

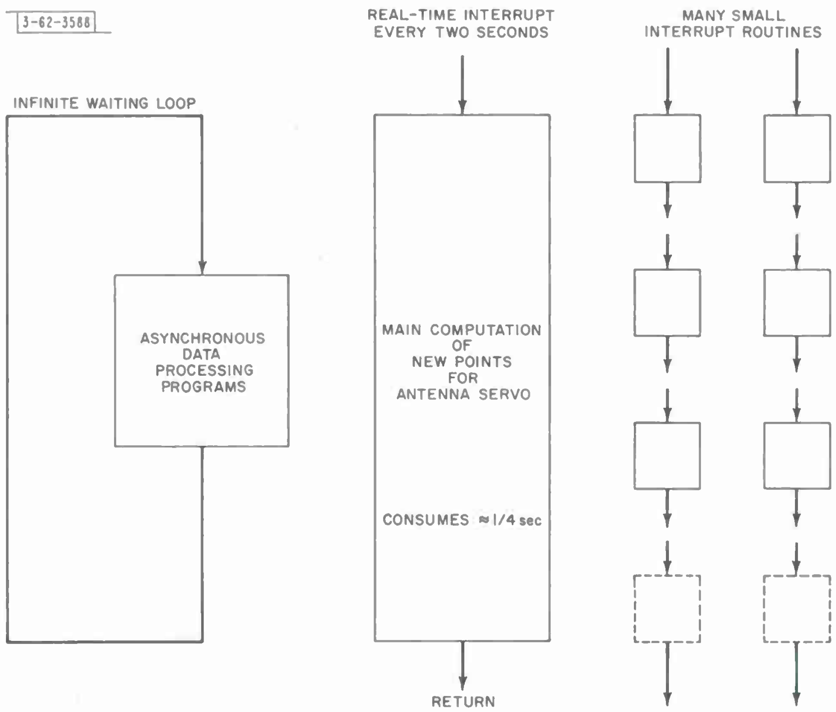

Fig. 16. Main control paths.

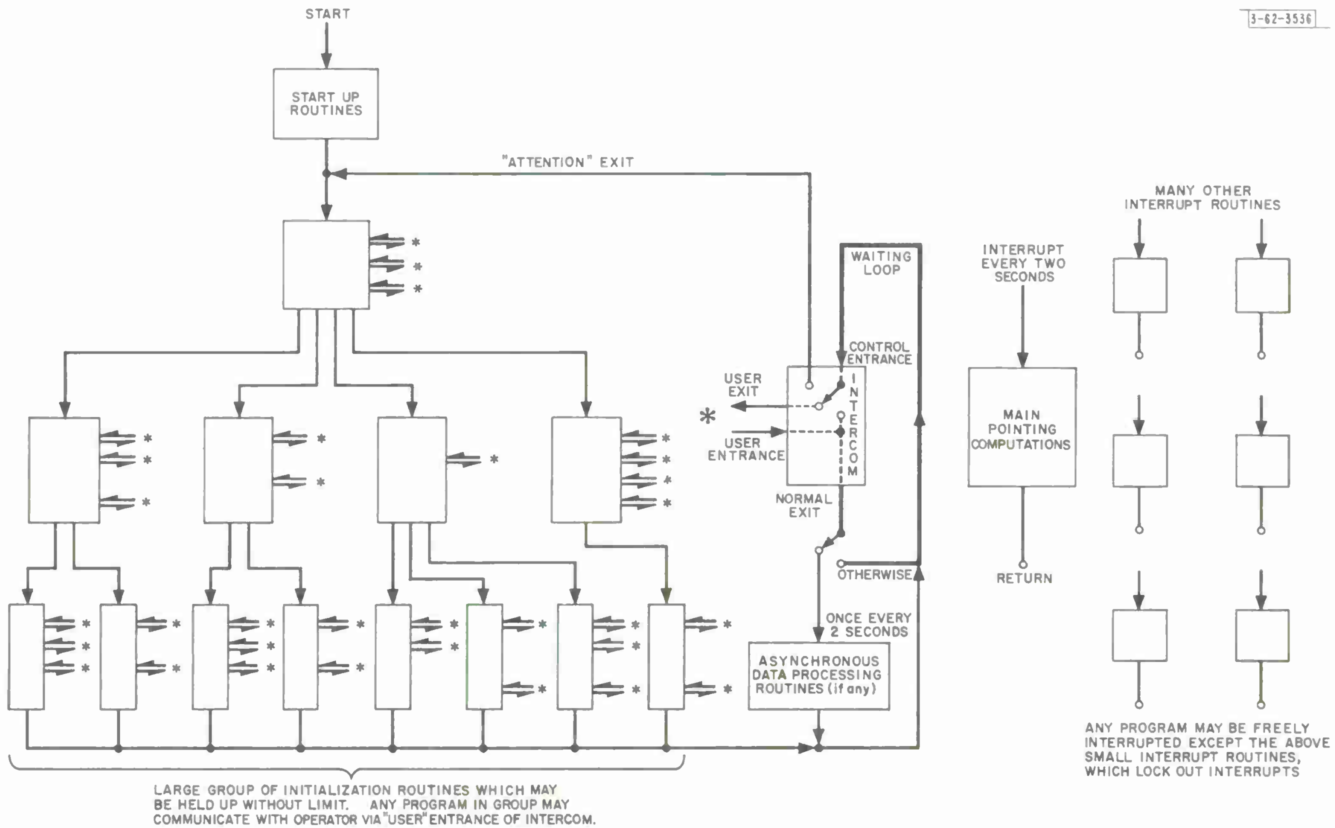

Fig. 17. Intercom logic.

loop is either just a "waiting" loop or it may contain any signal-processing programs that are asynchronous with the other pointing programs. The second path is the main ~1/4-second-long interrupt routine, initiated once every 2 seconds by external timing, which computes new points for the antenna servo (and may be interrupted by other interrupt routines). As a third path, there is a large group of (usually) short interrupt routines, which do everything else, including servicing the setup and completion of all in-out transfers. When these other interrupt routines are in control, they usually lock out other interrupts. The requirements for discourse with the operator can be added to this situation. Because a large number of programs in the pointing system require operator intervention, the control of such communication is centralized in a single program called "intercom," which can handle, in a standard way, formats, number conversion, keyboard and printer mechanics, error control conventions, and other processes. An alternative would have been to construct multiple (simpler) typing and keyboard input-output routines by each program that required operator communication. (Although the inclusion of intercom is still considered desirable, it complicates the control of the system.)

All major computation subprograms consist of a working section and an initialization section. Working sections of programs (which usually appear in the main, ~1/4-second, interrupt routine) are prevented from communicating with the operator. Initialization sections, on the other hand, operate asynchronously with the pointing computations and essentially steal time from the waiting loop. Any initialization section may communicate with the operator through the intermediary of the intercom program.[10] The natural sequence of operator discourse is such that only one initialization program at a time talks to the operator via intercom. Therefore, intercom is in a position to accept a "request" from an initialization program and to remember the details of that request until it is satisfied. Since the operator may answer questions at his own convenience or even deliberately delay an answer until such time as an action is required, this "memory" must operate over many seconds or minutes without any interference to the system. Initialization sections of programs are entered automatically when a new experiment is started, or they may be entered at the operator's convenience by using an attention symbol on the input keyboard. The sequence of questions and answers directs the transfer of control between various initialization routines until the operator has satisfied his control requirement.

Any program for typing a message to an operator, whether or not an answer is required, sets up an in-core message, in standard format, addressed to the intercom program. Intercom then arranges the actual type-out and waits for the operator's answer, if any. When such answers appear, they undergo format checking, limit checking, and number conversion prior to transmission to the requesting program. This entire process is under the control of the message left for the intercom program. Since at no point may the intercom program tie up the system or halt any other operations, these actions have to be interleaved and time-shared with the rest of the system. Considerable complexity is encountered in connection with system start-up or use of intercom by an asynchronous data-processing program. (These additional complexities will not be discussed in this report.) However, the intercom arrangements during normal real-time system operation are relatively straightforward (Fig. 17). Specifically, the intercom program has two entries and three exits. Through one entry, a user program leaves a specification for both the output and the input messages. Intercom then sets up the required printer output block transfer, after which it relinquishes control – not to the point from which

it was entered, but into the waiting loop. The second main entry to intercom is a control entry, wherein intercom is entered periodically (usually very frequently, but at least every 2 seconds). Upon such a control entry, intercom checks to determine whether or not anything interesting has happened; i.e.: Has the output transfer been completed? Have any input characters been received from the keyboard? Has an input keyboard message been completed (signified by a carriage return or a special attention symbol)? If nothing interesting has occurred, intercom again exits to the waiting loop. If events are proceeding normally, at some time, the question is completed, or the operator answers the question, and intercom discovers this. At this time, intercom exits with the completed question-answer sequence to the return point in the user program that made the request. Typically, that user program, or another to which control might then be transferred, might then make another request, etc. Thus, the operation of the two entries and two of the exits are described. The third exit is the one used when intercom discovers a special attention symbol. Such an occurrence transfers control to a particular set of operator discourse routines in order to determine what the operator desired. This is managed by the user routines when they send requests through intercom to the operator.

C. Interrupt Routines

In a sense, most of the work in the Haystack system is handled by the interrupt routines. Except for signal processing and initialization (including communication between man and machine), all programs are started as the result of some interrupt.

1. Pointing Computation

As previously stated, the routine for providing data to the antenna consists of a series of programs normally initiated by the periodic emptying of the azimuth buffer with the resultant internal interrupt.

2. Keyboard and Typewriter

The completion of an output message to the typewriter, or the input of a character from the keyboard, yields an interrupt. The main function of the interrupt handlers is to leave an appropriate mark for the main section of intercom. In the case of an input character, the (usually) necessary output of that character to the typewriter is performed.

3. Line Printer

The completion of an output line to the printer signals the printer interrupt section that the next line, if any, may be printed.

4. Real-Time Clock

The real-time clock generates an input every second. This interrupt is used to help sequence the repetitive console Nixie display of the right ascension and declination.

5. Doppler

In order to provide radar receivers with the most timely estimate of Doppler possible, the beginning of each main bang of the radar may be used to generate an external interrupt. After the appropriate Doppler is taken from a table prepared by the main point computation routine, it is sent to the radar receiver.

6. Target

At Haystack (and at the nearby West Ford antenna site), a radar return from a target may be used to generate an interrupt. This interrupt is used mainly by the satellite acquisition program (described in Sec. VI-B-4) to permit automatic search and target location. In a sense, this interrupt permits closing a tracking loop through the computer.

7. General-Purpose Data Input

A general-purpose channel exists for signal inputs (such as radiometric data). The use of and handling of an input interrupt is determined by the particular signal processing program in the system.

D. Data Processing Routines

In Figs. 16 and 17, the box labeled "asynchronous data processing routines" is entered every 2 seconds during the time that may remain after all pointing and initialization handling has been accomplished. Various types of plug-in program packages may occupy this position. As of 1 August 1965, radiometric analysis programs and planetary radar signal analysis programs had been successfully employed. Roughly 75 percent of the total computer time, or $1\frac{1}{2}$ second every 2 seconds, is available for such programs. This time may be employed by the data-processing program in either a synchronous or an asynchronous fashion. Specifically, the routine can plan to use less than $\sim 1\frac{1}{2}$ seconds every 2 seconds, and stay "coupled" to the pointing timing. Alternately, the routine could be planned to use all available time, with the expectation that it would be interrupted in the middle by the main 2-second interrupt in an unpredictable way.

Data-processing programs normally set up input data transfers from one or more signal sources and output data transfers to one or more real-time operator displays. Data-processing programs also normally leave raw and/or processed data in specified core locations for magnetic tape recording (the actual magnetic tape recording output transfers are arranged by a separate service routine of the system). Data-processing programs typically have working sections, which are represented logically in the boxes shown in Figs. 16 and 17. However, there usually are also initialization sections of these data-processing programs that would exist, such as one of the many initialization routines shown in Fig. 17. There may also be one or more small interrupt routines associated with the data-processing program, and such interrupt routines normally serve as in-out handlers.

The logical arrangement for including data-processing routines has been provided in a very general form. It is expected that a large number of routines may eventually be written as the experimental use of the facility develops and changes.

E. Recording and Logging

One of the four magnetic tape drives is habitually used as a primary system recording tape. In each frame a recording subroutine collects any records that have been left for it by other subprograms and sets up output block transfers to the magnetic tape. The pointing system generates a recording record each frame, and the data-processing programs, which may be running with the system, generate recording records at their convenience. The main pointing system record usually contains, as an option, the command angles that were sent to the antenna (250 per second), the actual antenna positions as measured by the encoders (also 250 per second),

TABLE I

PROGRAM SIZE

		Size (decimal)
Resident in-Core		
Control		2244
Intercom		4023
Timing		663
Right Ascension-Declination Display		783
Recording		374
Coordinate Conversion		1116
Interpolation		925
Acquisition		1484
Scan		1081
Intersite Coupling		226
Correction		1167
Servo Monitor and Strip Chart Recording		163
High-Speed Printer Logging		870
Debugging Aids		489
	Total	15608
Common Storage Tables		6656
	Total	22264
Celestial and Print Plug-in Programs		
Print (not used in real time)		3915
Fixed Celestial Coordinates		414
Fixed Azimuth and Elevation		152
Moon		2027
Star		3472
Sun		1753
Planet		1960
Belt (West Ford)		4061
Satellite		3879
Data Processing Plug-in Programs		
Radiometer I		2348
Radiometer II		3279
Planetary Radar		5308
Utility Programs (not part of real-time system)		
Preassembly Routines		2188
Post Assembly Routines		1323
System Tape-Making Routines		2276
Debugging Routines		1055
TOPS (Univac-furnished executive system)		3072

and the output Doppler data (also 250 per second). The record always contains a block of common storage locations sufficient to determine, in considerable detail, what the system was doing during that 2-second frame (see Ref. 15).

In addition to the magnetic tape recording, the on-line, high-speed line printer is commonly used for logging the full computer-operator conversation, as well as all other important changes in the status of the system. This on-line printer is also used by the data-processing program for real-time output of processed signal data. The combination of data output and system log provides a valuable record of site utilization. In a manner similar to magnetic tape recording, the use of the line printer is provided by a special subroutine, which accepts requests from other subprograms for output printing and then arranges the details in a standard fashion (see Ref. 15).

F. Storage and Timing

Table I gives the size of each program in the current system (April 1965). In terms of programming effort, the system totals about 60,000 decimal locations. The programs always in core occupy about 15600 registers. Additional common storage tables of about 6700 registers also remain in core. The largest plug-in program of the celestial computation class is the West Ford belt program, which occupies 4061 registers. The planetary radar program (the largest signal-processing program) occupies 5308 registers.

The time required for pointing computations is always well less than $\frac{1}{2}$ second every 2 seconds (25 percent). As an example, the timing of the main computation routine with the planet program as the celestial computation choice is given in Table II.

G. Planning Mode

A system that can generate real-time pointing data can, with a few modifications, also generate non-real-time data. At Haystack, this generation of non-real time data has been implemented as a simulated run. When the simulated-run option is chosen, the antenna would normally be disconnected and several parameters would become available. One can enter a fictitious time instead of the real time. The program, still operating at a 2-second cycle time,

TABLE II
PROGRAM TIMING

Program	Time (msec)
Right Ascension-Declination Display	15.4
Planet	10.0
Right Ascension-Declination Scan	0.4
Coordinate Conversion	27.8
Azimuth-Elevation Scan	0.8
Correction	0.8
Acquisition	0.8
Interpolation	152.0
Intersite Coupling	15.4
Recording	0.8
Total	224.2

```
LES II                                                                      FRIDAY          MAY 21, 1965   SATELLITE SYSTM

 HH MM SS RA(DEG)  DEC(DEG)    DISTANCE     DISTDOT      RADOT        AZIM      ELEV      CAZIM    TRUERANGE  RA(HMS)        DEC(DMS)
 19 26 55  42.7534  10.4070    2.83677363 -0.80338   1.8777370 254.2753  11.1016 254.2753   2.4691207  2 51   0.83  10 24 25.3

           SRA       SDEC      CRANGE  RANGEDOT  DECDOT   SAZIM     SELEV     CELEV    SIDERTIME
           42.7534   10.4070    525105 -0.77816 -1.1089678 254.2753  11.1016  11.2020   99.4627


 TIME   INCOMING INCOMING COMMAND  COMMAND   RECVD R/A    RECVD DECLN  COMND R/A    COMND DECLN COMND DOPLR MODES
 SECS   AZIMUTH ELEVATION AZIMUTH ELEVATION HH MM SS.SS DDD MM SS.S   HH MM SS.SS DDD MM SS.S CYCLES/SEC. ABCDE
 0.000*254.2751  11.2019 254.2751  11.2019  2 51 15.25  10 27 49.7   2 51 15.25  10 27 49.7      74567
 0.400*254.2710  11.2012 254.2710  11.2012  2 51 16.15  10 27 39.2   2 51 16.15  10 27 39.2      74572
 0.800*254.2669  11.2006 254.2669  11.2006  2 51 17. 5  10 27 28.6   2 51 17. 5  10 27 28.6      74578
 1.200*254.2628  11.2006 254.2621  11.2006  2 51 18. 4  10 27 19.5   2 51 18.14  10 27 18.0      74583
 1.600*254.2580  11.1999 254.2580  11.1999  2 51 19. 4  10 27  7.5   2 51 19. 4  10 27  7.5      74588

LES II                                                                      FRIDAY          MAY 21, 1965   SATELLITE SYSTM

 HH MM SS RA(DEG)  DEC(DEG)    DISTANCE     DISTDOT      RADOT        AZIM      ELEV      CAZIM    TRUERANGE  RA(HMS)        DEC(DMS)
 19 26 57  42.7753  10.3943    2.83630705 -0.80377   1.8782773 254.2538  11.0986 254.2538   2.4686687  2 51   6. 8  10 23 39.5

           SRA       SDEC      CRANGE  RANGEDOT  DECDOT   SAZIM     SELEV     CELEV    SIDERTIME
           42.7753   10.3943    525009 -0.77843 -1.1094618 254.2538  11.0986  11.1991   99.4711


 TIME   INCOMING INCOMING COMMAND  COMMAND   RECVD R/A    RECVD DECLN  COMND R/A    COMND DECLN COMND DOPLR MODES
 SECS   AZIMUTH ELEVATION AZIMUTH ELEVATION HH MM SS.SS DDD MM SS.S   HH MM SS.SS DDD MM SS.S CYCLES/SEC. ABCDE
 0.000*254.2538  11.1992 254.2538  11.1992  2 51 20.49  10 27  4.8   2 51 20.49  10 27  4.8      74593
 0.400*254.2497  11.1985 254.2497  11.1985  2 51 21.39  10 26 54.3   2 51 21.39  10 26 54.3      74598
 0.800*254.2456  11.1978 254.2449  11.1978  2 51 22.29  10 26 43.8   2 51 22.39  10 26 42.2      74604
 1.200*254.2408  11.1971 254.2408  11.1971  2 51 23.28  10 26 31.7   2 51 23.28  10 26 31.7      74609
 1.600*254.2367  11.1964 254.2367  11.1964  2 51 24.18  10 26 21.2   2 51 24.18  10 26 21.2      74614
```

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Fig. 18. Output of print program.

produces data for the selected body. These data can be seen in the right ascension-declination console Nixie lights and in the azimuth-elevation console Nixie lights.

The frame size can be made any integral number of seconds from 0 to about 3 hours. Now, every 2 seconds the internal time in the computer is indexed by the frame size. Thus, one may obtain a speeding up of the (simulated) movement of the antenna in tracking the selected object. The 0, or stationary case, has been used in generating drift scans for radiometer work (in a drift scan, earth motion moves the beam from a fixed antenna through a target). The cycle time of the system can also be speeded up in the simulated mode, so that a complete set of data for each frame can be generated in approximately $\frac{1}{8}$ second, instead of 2 seconds. In this fast mode, ephemerides for the moon for every hour for a year may be generated in less than an hour (see Ref. 15).

H. Printing Mode

The generation of data in real-time operations, and especially in simulated runs, would not be very worth while if some means did not exist for recovering the data. At Haystack, normally all data are recorded – or at least all data, except the 4-msec interpolated data. At the end of an experiment or of a planning run, or at one's leisure, the recording may be printed. Figure 18 is an example of printed output. (See Ref. 25 for a description of a general printer utility program.)

The print program may be selected via the familiar attention route and it operates in that portion of core storage normally allotted for celestial computation programs. For selected time intervals, the system will print for each frame:

(1) Time (real or simulated as the case may be),
(2) Geometric celestial coordinates and rates of change,
(3) Celestial coordinates with scan added,
(4) Radar coordinates and range rate,
(5) Radar coordinates with scan added,
(6) Radar coordinates corrected for refraction and other errors,
(7) Sidereal time.

In addition, every n^{th} interpolated azimuth and elevation command and actual (shaft encoder) azimuth and elevation, as well as the right ascension and declination corresponding to the actual antenna position, may be printed.

I. Mechanics of Program Construction

1. Coding

All the Haystack programs are written in machine language. SPURT III, the Univac assembly system, ultimately provides a binary object program. During the period of initial program construction, most of the programmers were located at the main buildings of Lincoln Laboratory, which is some 25 miles from the Haystack site. Because a complete card punching and computational facility was available at the Laboratory, it was decided to use Hollerith cards as the symbolic program medium rather than paper tape, the usual input to SPURT. Lincoln Laboratory printed its own programming pads, which have a format quite different from that of Univac. The cards punched from these forms are loaded onto magnetic tape by an IBM 1401.

KEY1 ON=NO LOG. KEY2 ON= DUP INPUT... ENTER DATE ETC.

NEW SYSTEM TAPE ....APRIL 28, 1965
I/C(1) B/S(2) CCP(3) DPP(4)

1
B/A(UNLESS 6000)

SYSTEM NAME	PROGRAM NAME	PROGRAMMER+DATE	FIRST LOCTN.	LAST LOCTN.	RUN ENTRY	INIT ENTR
MCPGM	MCP	JDD*26APR65	06000	12161	06002	06002
KYBRD	NTERCØM	ADAMS-ASSØC*5DEC64	12163	22051	12165	12167
CORCT	CØRCT	CLARK*9JUNE64	22053	24271	24106	22055
INTER	INTER	TEØSTE*11/10/64	24273	26127	25564	24275
AESCN	DUMSCAN	W.R.CRØWTHER*JAN.28*	26131	26143	26135	26133
RECRD	RECØRDING	JDD+AAM*04/28/65	26145	26732	26237	26147
PRLOG	LØGGING	S.J.WHITE*01/04/65	26734	30501	26743	26736
RADEC	RADEC	PSTYLØS20APRIL65	30503	32121	30653	30505
DYDMP	DYDMPPGM	S.J.WHITE*06/23/64	32123	32543	32125	32307
CHCOR	CHANGECØRE	S.J.WHITE*MAR.25*64	32545	32651	32547	32547
ADSCN	SCAN	PCRØWTHER*26JAN65	32653	34730	33600	32656
COCON	CØCØN	PSTYLØS*20APRIL65	34732	37065	35442	34734
CHPAR	PARAMETER	MATHIASEN*3/26/65	37067	37311	37071	37073
ACQUI	ACQUI	R.TEØSTE*4/9/65	37313	42226	37645	37315
PLANP	PLANNER	JDD*6/26/64	42230	42351	42236	42232
WFORD	WESTFØRD	JDD*1/29/65	42353	42714	42402	42355
TIMEP	TIMING	JDD*4/21/65	42716	44144	43265	42720
PLOTP	PLØTP	R.TEØSTE*4/9/65	44146	44410	44364	44150

EOF
I/C(1) B/S(2) CCP(3) DPP(4)

2
FWA

LWA

B/S DONE..
I/C(1) B/S(2) CCP(3) DPP(4)

3
B/A OTHER THAN 44412

PRINT	PRINTØUT	SATTEST*1/28/65	44412	54124	44414	44414
FRADC	FXRADEC	MATHIASEN*2/17/65	44412	45247	44414	44417
MOONP	MØØNTRACK	HJF+DMH*11/30/64	44412	50364	44646	44414
STARP	STARTRACK	FRACTMAN*1/26/65	44412	53231	44473	44414
SUNPG	SUNTRACK	HJF+DMH*11/30/64	44412	47742	44613	44414
PLNET	PLANETRACK	HJF+DMH*11/30/64	44412	50261	44645	44414
FXANE	FXAZEL	MATHIASEN*04/20/65	44412	44641	44414	44417
BELTP	BELTP	PØNTØN*290CT64	44412	54346	45256	44414
SATEL	SATEL	MCQUILKIN*5FEB65	44412	54060	52333	52304

EOF
EOF(1)

CCPGMS DONE...
I/C(1) B/S(2) CCP(3) DPP(4)

4
B/ OTHER THAN 54350

RDMTR	RADIØMETER	P.STYLØS*3/18/65	54350	61023	54616	54352
PDMTR	RDMTRSCAN	PCRØWTHER*30MAR65	54350	62666	54616	54352

EOF
EOF(1)

1
DPPGMS DONE...

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Fig. 19. Log of tape-making procedure.

At Haystack, a program takes this tape and writes another tape in the SPURT format for input to the assembly system. (It also has the small, but advantageous, capability of handling a decimal fraction pseudo operation that SPURT does not have.) The assembly output at Haystack is a relocatable binary tape and a listing. The listing is either made directly on the local high-speed printer or indirectly on magnetic tape (with some added niceties, such as page numbering) for printing via the 1401.

2. Symbolic Assignments

A set of registers, known as common storage, has been set aside for certain quantities that are used by more than one program, or that are convenient to have in a central location. Examples of such quantities include the celestial coordinates of the point to which the antenna is directed, the radar coordinates of that point, the interpolated values of azimuth, elevation, and Doppler, and many program control switches. These registers have symbolic names which, together with their absolute locations, are typed on an allocation paper tape, which is then compiled with each system program. The use of these symbolic names in programs is therefore restricted to an actual reference to common storage.

References to other absolute locations, such as input and output channels, and interrupt entrance registers, are also made symbolically. Equivalence statements at the beginning of the program establish the numerical values.

3. Making a System Tape

It was indicated earlier that the entire program system is stored on a single "bootstrap" magnetic tape for easy system start. Since such a program system is continually changing and growing, a procedure was needed for systematically producing such master bootstrap tapes (see Ref. 26).

The individual programs are stored on the following three types of master program tapes: one type contains those programs that are always in core; the second, all the celestial coordinate computation programs and the general print program; and the third, all the signal-processing programs. If a program is to be replaced on or added to one of these tapes, the master program tape and the tape containing the new program are both mounted. An "updater" program then makes a new tape containing the revised set of programs. Also, a program may be deleted from the master program tape.

The system "loader" program operates next. It reads into core the programs from the master in-core tape. (These programs are in relocatable binary.) In reading, starting at some chosen base location, they are put into absolute binary with all addresses suitably modified. When all the in-core programs are loaded, the first record of the new bootstrap tape is written with the core image. (For later use by the real-time system control program, a table of names and entries of the in-core programs is made up and put in common storage as part of this first record.) The celestial computation master tape is next read in. Each celestial program is assigned the same starting address – the next address after the last in-core program. After each new program is read in, it is also added as a separate record on the core image record on the new bootstrap tape. Finally, the data-processing programs are handled similarly. For record keeping, a log of the system programs on the bootstrap tape is also printed on the console typewriter. Extracts from such a log are shown in Fig. 19.

VI. STARS AND SATELLITES

To illustrate the detailed workings of a few programs in the system, in this section two typical experiments will be followed through several programs. These experiments include radiometric study of a star and satellite acquisition.

A. Radiometric Study of a Star

1. Experiment Setup

Suppose that a radio astronomer wishes to make radiometric measurements of the radio star Cassiopeia A. He selects a right ascension scan, centered on the star of, say, 0°.25 with a period of 8 minutes. Lastly, he brings in the radiometer program and sets the parameters it requests (see Fig. 11).

2. Star Program

The star program[17] finds in its tables that for Cassiopeia A,

$$\alpha_o = 23^h\, 21^m\, 36\overset{s}{.}1 \quad ,$$

$$\delta_o = 58°\, 35'\, 48''\!.0 \quad ,$$

Epoch = 1960.0

Suppose that the experiment is being run on 19 May 1965. The mean coordinates are then corrected for precession to 1965.0 (no correction is made for proper motion). A reduction from mean to apparent place, correcting for precession, nutation, and annual aberration is then made to 19 May to find the right ascension and declination of date, α_c and δ_c. See Appendix B and Refs. 17 and 27 for mathematical details.

3. Scan Program

The quantities α_c and δ_c are modified by the scan program. In particular, the scanned right ascension is

$$\alpha_s = \alpha_c + f_{S,p}(t - t_o) \quad .$$

In this example, the amplitude S is 0°.25, and the period p is 8 minutes. Since no scan has been requested in declination,

$$\delta_s = \delta_c \quad .$$

The function $f_{S,p}$ is triangular with rounded vertices (Fig. 20). The exact shape is determined by considerations of the antenna. The maximum velocity is 3° per second, and the maximum acceleration is 1° per sec^2. This combination leads to a turn-around time of 6 seconds when the antenna is going at maximum velocity. Thus, 6 seconds was chosen as standard at every velocity (up to 3° per second), and the acceleration is taken as 1/3 the velocity in magnitude. If the period is p and the amplitude is S, the acceleration may be written as

$$|\text{accel}| = \frac{4}{3}\,\frac{S}{p-6}\ \text{degrees/sec}^2$$

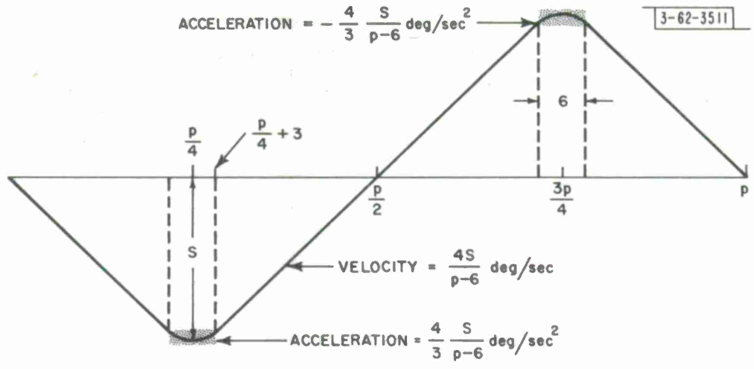

Fig. 20. Scan pattern, $f_{S,p}$.

during the 6 seconds allowed for antenna reversal. The velocity is

$$|\text{veloc}| = \frac{4S}{p-6} \text{ degrees/sec} \quad .$$

In this example, the magnitude of the velocity is 1/474° per second and of the acceleration during reversal is 1/1322° per sec^2 (or approximately $0^s\!.5$ in right ascension per second and $0^s\!.6$ per second per second).

4. Coordinate Conversion[22]

The apparent sidereal time at 0^h U.T. for every day of the year is recorded on the Ephemeris Tape. The apparent sidereal time ST at time t of the day is found by linear interpolation. The local hour angle of the site is

$$\Omega_E = ST + \lambda_E \quad ,$$

where λ_E is the (East) longitude of the site.

For a site at geodetic latitude φ_E, the azimuth is

$$A = \tan^{-1} \frac{\cos\delta_s \sin(\alpha_s - \Omega_E)}{\sin\delta_s \cos\varphi_E - \cos\delta_s \sin\varphi_E \cos(\alpha_s - \Omega_E)} \quad ,$$

and the elevation is

$$E = \sin^{-1} [\cos\delta_s \cos\varphi_E \cos(\alpha_s - \Omega_E) + \sin\delta_s \sin\varphi_E] \quad .$$

5. Radiometer

As the antenna moves back and forth across the star, the received energy rises and falls. It is the function of the radiometer program to process the data received and to provide a suitable print and plot of them.[28]

For a radiometer receiver, three different modes are used: calibrate, base, and observe. With the antenna offset from the star, a calibrate noise signal is fed into the antenna waveguide for some period, typically a minute. The average signal R_c is computed. The receiver is next put in the base mode (the calibrate signal is turned off) and the average signal R_B over the base period (again typically a minute) is computed. The receiver is next put in the observe mode, and the antenna scans back and forth across the star. The averaged signals R_o over

RDMTR 05/19/65

TIME	RIGHTA	DECLIN	T(1)	T(2)	DEL(1)	DEL(2)	-2	0 2 4 6
20 31 12	23 21 58	58 48 53	0001.33	0001.21	00.196	00.121	I	1
20 31 16	23 20 38	58 40 32	0001.78	0001.73	00.172	00.150	I	1
20 31 22	23 20 42	58 40 31	0001.97	0001.90	00.084	00.089	I	1
20 31 26	23 20 46	58 40 44	0001.76	0001.73	00.090	00.131	I	1
20 31 32	23 20 49	58 40 50	0001.81	0001.62	00.125	00.132	I	OX
RA SCAN								
20 31 38	23 20 50	58 40 43	0002.06	0001.77	00.161	00.026	I	O X
20 31 42	23 20 54	58 40 43	0002.00	0001.90	00.099	00.081	I	OX
20 31 48	23 20 56	58 40 43	0001.84	0001.92	00.027	00.123	I	1
20 31 52	23 20 59	58 40 43	0002.18	0001.93	00.131	00.150	I	OX
20 31 58	23 21 01	58 40 46	0002.02	0001.88	00.189	00.130	I	OX
20 32 02	23 21 04	58 40 42	0001.67	0001.75	00.157	00.055	I	1
20 32 08	23 21 07	58 40 44	0001.80	0001.79	00.096	00.098	I	OX
20 32 12	23 21 10	58 40 42	0001.97	0001.80	00.076	00.058	I	1
20 32 18	23 21 12	58 40 42	0001.73	0001.71	00.051	00.101	I	1
20 32 22	23 21 15	58 40 41	0001.76	0001.86	00.101	00.079	I	XO
20 32 28	23 21 17	58 40 43	0001.97	0001.64	00.079	00.097	I	OX
20 32 32	23 21 20	58 40 41	0001.62	0001.71	00.163	00.128	I	1
20 32 38	23 21 23	58 40 47	0001.65	0001.81	00.062	00.074	I	XO
20 32 42	23 21 26	58 40 42	0001.57	0001.52	00.131	00.151	I	1
20 32 48	23 21 28	58 40 42	0001.74	0001.86	00.115	00.109	I	XO
20 32 52	23 21 31	58 40 44	0001.93	0001.75	00.133	00.086	I	OX
20 32 58	23 21 33	58 40 40	0002.02	0001.82	00.087	00.185	I	OX
20 33 02	23 21 36	58 40 43	0002.26	0002.12	00.143	00.111	I	OX
20 33 08	23 21 38	58 40 43	0002.53	0002.36	00.128	00.096	I	OX
20 33 12	23 21 40	58 40 46	0003.31	0002.89	00.073	00.104	I	O X
20 33 18	23 21 43	58 40 44	0003.88	0003.77	00.182	00.220	I	OX
20 33 22	23 21 47	58 40 46	0004.98	0004.50	00.054	00.098	I	O X
20 33 28	23 21 49	58 40 44	0005.59	0005.33	00.080	00.167	I	OX
20 33 32	23 21 51	58 40 44	0006.46	0005.89	00.199	00.178	I	O X
20 33 38	23 21 54	58 40 45	0006.85	0006.19	00.109	00.077	I	O X
20 33 42	23 21 57	58 40 45	0007.06	0006.38	00.066	00.105	I	O X
20 33 48	23 22 00	58 40 47	0007.06	0006.62	00.107	00.100	I	O X
20 33 52	23 22 02	58 40 45	0006.92	0006.45	00.115	00.129	I	O X
20 33 58	23 22 05	58 40 42	0006.67	0006.13	00.097	00.113	I	O X
20 34 02	23 22 08	58 40 49	0005.84	0005.49	00.147	00.189	I	O X
20 34 08	23 22 11	58 40 43	0005.45	0005.08	00.206	00.113	I	O X
20 34 12	23 22 13	58 40 43	0004.96	0004.70	00.220	00.129	I	OX
20 34 18	23 22 16	58 40 45	0004.20	0003.96	00.156	00.113	I	O X
20 34 22	23 22 19	58 40 41	0003.93	0003.48	00.163	00.125	I	O X
20 34 28	23 22 21	58 40 46	0003.24	0003.05	00.176	00.153	I	OX
20 34 32	23 22 23	58 40 47	0002.96	0002.70	00.179	00.169	I	OX
20 34 38	23 22 26	58 40 48	0002.63	0002.68	00.123	00.097	I	1
20 34 42	23 22 29	58 40 45	0002.55	0002.73	00.149	00.174	I	XO
20 34 48	23 22 32	58 40 45	0002.58	0002.33	00.131	00.084	I	OX
20 34 52	23 22 34	58 40 44	0002.31	0002.41	00.105	00.219	I	XO
20 34 58	23 22 37	58 40 45	0002.47	0002.15	00.102	00.074	I	O X
20 35 02	23 22 39	58 40 35	0002.28	0002.30	00.116	00.058	I	1
20 35 08	23 22 42	58 40 42	0002.30	0002.42	00.045	00.100	I	XO
20 35 12	23 22 45	58 40 50	0002.35	0002.37	00.090	00.071	I	1
20 35 18	23 22 47	58 40 42	0002.22	0001.83	00.193	00.077	I	O X
20 35 22	23 22 50	58 40 43	0002.11	0002.20	00.072	00.069	I	XO
20 35 28	23 22 52	58 40 45	0002.13	0002.21	00.112	00.080	I	XO
20 35 32	23 22 54	58 40 45	0002.36	0002.15	00.146	00.086	I	OX

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Fig. 21. Radiometer output.

each interval of a length set by a knob on the receiver are computed. The estimated standard deviations S are also found in all three modes.*

The quantities R_c and R_B give the slope of antenna temperature vs signal amplitude r seen by the computer. This is essentially linear. The calibration and base temperatures T_c and T_B have been determined previously and entered into the radiometer program.

The quantities

$$V = \frac{T_c}{R_c - R_B} R_B + T_B \quad ,$$

$$\Delta V = \frac{T_c}{R_c - R_B} S_B \quad ,$$

$$\Delta C = \frac{T_c}{R_c - R_B} S_c \quad ,$$

are computed to give the observed base temperature and standard deviations of base and calibrate temperatures.

For the observed average signal R_o, the quantity

$$T = \frac{T_c}{R_c - R_B} (R_o - R_B) \quad ,$$

which is seen to be actually the temperature above the base temperature, is found. The standard deviation of the temperature is also found as

$$\Delta T = \frac{T_c}{R_c - R_B} S_o \quad .$$

The printout not only gives the base and calibrate temperatures and standard deviations of each of two receivers, but also at the end of each averaging period a printout time, right ascension, declination, temperature (above the base) and standard deviations for each receiver, plus a plot of temperature. In Fig. 21, receiver 1 is denoted by X, receiver 2 by 0, and a coincidence of both by 1.

B. Satellite Acquisition

1. Experiment Setup

In this example of satellite acquisition, the satellite LES-2 is tracked. After bringing in the satellite program, the latest known orbit parameters are entered. Since these are not yet known exactly, the acquisition program is also activated and told to scan in a box 2° by 0°.5, where the longer dimension is parallel to the nominal orbit, because of the belief that the major orbital parameter error is in time (Fig. 12).

---

*

$$R = \frac{1}{N} \sum_{i=1}^{N} r_i \quad , \quad S = \sqrt{\frac{\sum_{i=1}^{N} r_i^2}{N(N-1)} - \frac{R^2}{N-1}} \quad , \quad N > 1 \quad .$$

2. Satellite Program

For its orbit parameters, the satellite program uses mean elements of the type the Smithsonian Astrophysical Observatory (SAO) first published and which are now coming into more universal use. (See Refs. 14, 29, 30, and 31.) The parameters are:

n = anomalistic mean motion,

e = eccentricity,

ω = argument of perigee,

i = inclination,

Ω = right ascension of ascending mode,

T_o = epoch of parameters,

M_o = mean anomaly at T_o,

and such derivatives as are known. Actually, all the parameters are of the form

$$Y(t) = \sum_{i=o}^{k} c_i (t - T_o)^i \quad ,$$

where

$$c_i = \frac{1}{i!} \left. \frac{d^i Y}{dt^i} \right]_o \quad .$$

All parameters are first updated to the beginning of the current day in order to avoid round-off problems necessitated by carrying a large number of bits for the integral part of time (see Appendix C). The semi-major axis is calculated from the other parameters. Osculating elements are derived from the mean elements, and from these are obtained the radius ρ, right ascension α, and declination δ, for each frame, as well as the rates of change $\dot{\rho}$, $\dot{\alpha} \cos\delta$, and $\dot{\delta}$.

3. Coordinate Conversion Program

The simplified expressions for azimuth and elevation that may be used when the distance to the object is infinite cannot be used for satellites. The radar Cartesian coordinates of the satellite x, y, and z are found by appropriate coordinate axis rotations and translations (see Appendix D). The range is then simply

$$R = \sqrt{x^2 + y^2 + z^2} \quad ,$$

the azimuth is

$$AZ = \tan^{-1} \frac{x}{y} \quad ,$$

and the elevation is

$$EL = \sin^{-1} \frac{z}{R} \quad .$$

Differentiating R leads to an expression for range rate.

4. Acquisition

The acquisition program,[32] which works hand in hand with the interpolation program, takes the values of azimuth and elevation (after correction) and suitably modifies these to obtain a search pattern (Figs. 22 and 23).

The antenna first moves along the nominal satellite trajectory a length specified during initialization (in this example, 2°). It next moves normal to the trajectory 0.9 beamwidth, then moves back parallel to the nominal trajectory the specified length, next moves normal to the trajectory until it is 0.9 beamwidth on the other side of the trajectory, and finally moves up parallel to the trajectory. The width of the box keeps getting larger by 0.9 beamwidth each time a reversal occurs until the specified width (in this example, 0.°5) is reached. The box, of course, stays centered on the satellite. All these antenna movements are made at its maximum speed and acceleration consonant with precision.

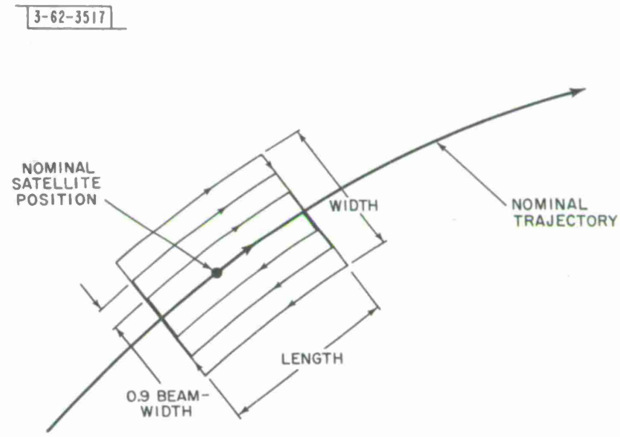

Fig. 22. Raster scan.

If a return is found, the antenna is held at the point of return for 6 seconds. If returns continue, this procedure is repeated (noting that one continues to move with the nominal position with biases added in azimuth and elevation). Thus, if the interval between hits does not at any time exceed 6 seconds, the antenna effectively stays with the satellite without any additional scan imposed.

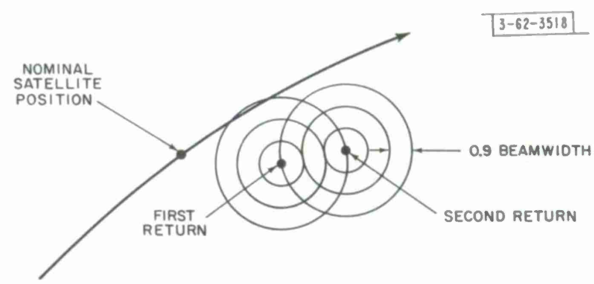

Fig. 23. Circular scan.

If the satellite is not found, a series of concentric search circles of radii 0.9, 1.8, and 2.7 beamwidths is generated until the satellite is found, at which point it is again held for 6 seconds. If the satellite is not found again in the search circles, a false alarm is presumed, and the raster search is continued.

When the satellite is definitely found (the criterion is three more hits during the circular scan), a time correction is given to the satellite program, and appropriate corrections to elevation and azimuth biases are made to account for errors normal to the trajectory.

VII. COMMENT

Early efforts on the Haystack computer control system began in late 1960, and the system was operated for the first time in late 1964. The pointing system itself and the subsystems, which are closely connected with the Univac 490 computer, probably involved a hardware effort of eight man-years and a software effort of nine man-years. Projects of such size and time span must typically cope with complex administrative, economic, and personnel problems. As one result, the pointing system is somewhat more complicated than it might otherwise have been, and it contains redundancies and elaborations that might have been avoided in a shorter, more tightly

controlled project. However, the pointing system works well, and can be expected to serve the Haystack facility for many years.

Despite the fact that the computer provides about 75 percent of its total time as an available asset for signal-processing programs, the site will undoubtedly need additional computer capacity at some future time. The real-time signal processing needs of such a facility increase extremely rapidly in the face of improvements in radar and radiometric techniques. If such additional computer capacity is obtained, it could be connected to the Univac 490 in an intimate fashion. The pointing system programs will, in general form, remain quite stable. Additions may be expected along the lines of automatic "over-all" procedures. For example, a program is now being designed to use a box scan in right ascension and declination, and to determine the point in that box of maximum received radiometric energy. Such a program addition simply makes use of existing program subroutines of the system and adds a small control program. Similar additions may be expected in satellite handling and in radar astronomy.

Perhaps the single, most obvious change to be incorporated, if this system should be updated, would be to close the servo loops within the computer and thereby eliminate most of the special-purpose digital hardware in the azimuth and elevation systems. Such a change would have been difficult to incorporate in the present system in view of the computer speeds available in 1961, but it would be relatively straightforward in 1965.

APPENDIX A
CHARACTERISTICS OF UNIVAC 490 COMPUTER

The Univac 490 computer is a binary arithmetic, parallel transfer, solid state machine. The word length is 30 bits including sign. Arithmetic is one's complement, single precision, fixed point. There are 7 hardware index registers and 32,768 registers of core memory, the first 16 registers of which may be replaced by a wired-in bootstrap program. The memory is random access with a 6-μsec cycle time. There are 62 basic instructions, including arithmetic, logical, jump, index, and in-out commands. With modifiers which enable instructions to refer to whole or half words, or to the arithmetic registers, and to skip on various conditions, the repertoire may be said truly to consist of over 25,000 instructions. The average instruction time is 10 μsec.

There is a priority structure of 14 input and 14 output channels, fully buffered, and each with internal interrupt capability to signal the end of a block transfer. In addition, there is an external interrupt on each channel which may be used for any purpose (not necessarily connected with the input or output on that channel). An in-out transfer takes two memory cycles. The maximum rate of transfer is one every 18 μsec.

APPENDIX B
STAR POSITION CORRECTION

The correction for precession in reducing mean positions from one epoch to another is made by the standard formulas:[17,27]

$$\sin\delta = \cos\Theta \sin\delta_o + \sin\Theta \cos\delta_o \cos(\alpha_o + \zeta_o) \quad ,$$

$$\cos\delta \sin(\alpha - z) = \cos\delta_o \sin(\alpha_o + \zeta_o) \quad ,$$

where

$$\zeta_o = (2304''.250 + 1''.396 T_o)\, T + 0.302 T^2 \quad ,$$

$$z = \zeta_o + 0''.791 T^2 \quad ,$$

$$\Theta = (2004''.682 - 0''.853 T_o)\, T - 0''.426 T^2 \quad ,$$

where T_o is the number of tropical centuries from 1900.0 to the initial epoch and $T_o + T$ is the number of tropical centuries from 1900.0 to the final epoch, the beginning of the current tropical year.

The apparent positions corrected for precession, nutation, and annual aberration are found from

$$\alpha_c = \alpha + Aa + Bb + Cc + Dd + J \tan^2\delta \quad ,$$

$$\delta_c = \delta + Aa' + Bb' + Cc' + Dd' + J' \tan\delta \quad ,$$

where the star constants are computed from

$$a = m/n + \sin\alpha \tan\delta, \qquad a' = \cos\alpha,$$
$$b = \cos\alpha \tan\delta, \qquad b' = -\sin\alpha,$$
$$c = \cos\alpha \sec\delta, \qquad c' = \tan\epsilon \cos\delta - \sin\alpha \sin\delta,$$
$$d = \sin\alpha \sec\delta, \qquad d' = \cos\alpha \sin\delta,$$

and

$$\tan\epsilon = 0.43365269 - .00000270t,$$
$$t = \text{present year} - 1963,$$
$$m/n = 2.29887 + 0.0000237Y,$$
$$Y = \text{present year} - 1900.$$

A, B, C, and D are Besselian day numbers. J and J' are second-order day numbers. These numbers, together with other astronomical data such as planetary ephemerides and sidereal time, are available on punched cards from the Nautical Almanac Office of the United States Naval Observatory. These data are stored on magnetic tape by an Ephemeris Tape program written for the IBM 7094. In particular, the Besselian day numbers are recorded for each day of the year and the second-order day numbers are recorded for every tenth day and every hour of right ascension.

APPENDIX C
SATELLITE COORDINATE COMPUTATION

With mean elements of the form

$$Y(t) = \sum_{i=o}^{k} c_i (t - T_o)^i \quad ,$$

the updating is done by changing the polynomial expression to

$$Y(\tau) = \sum_{j=o}^{k} b_j \tau^j \quad ,$$

where

$$b_j = \sum_{i=j}^{k} c_i \binom{i}{j} (T - T_o)^{i-j} \quad ,$$

with T the beginning of the current day. Thus, $t \equiv \tau \bmod T$.

If the equinox is not of date, but of 1950.0, Ω is corrected by adding $3\overset{\circ}{.}508 \times 10^{-5}$ (MJD-33281), where MJD is the modified Julian Day corresponding to T.*

The semilatus rectum is first approximated by

$$p \approx \left(\frac{GM}{n^2}\right)^{1/3} (1 - e^2) \quad .$$

The semimajor axis is then taken as

$$a = \left(\frac{GM}{n^2}\right)^{1/3} \left[1 - \frac{A_2}{p^2} \left(1 - \frac{3}{2} \sin^2 i\right) \sqrt{1 - e^2}\right]^{1/3} \quad .$$

Here, G is the gravitational constant and M is the mass of the earth. For a in earth radii and n in revolutions per day, GM is 290.4788. The second harmonic of the earth potential A_2 is 0.001624.

The eccentric anomaly E is found by solving Kepler's equation[29]

$$M = E - e \sin E \quad .$$

This is done iteratively,

$$M_i = E_i - e \sin E_i \quad ,$$

$$\Delta E_i = \frac{M - M_i}{1 - e \cos E_i} \quad ,$$

$$E_{i+1} = E_i + \Delta E_i \quad .$$

When $|\Delta E_i| < \epsilon$, the iteration stops. This is extremely rapid, one or two iterations sufficing when E_o is a good guess. In the steady state, E_o at time t is expressed as

---

*MJD = Julian Day −2,400,000.5.

$$E_o(t) = E(t-\Delta t) + [E(t-\Delta t) - E(t-2\Delta t)] \quad ,$$

where $E(t-\Delta t)$ and $E(t-2\Delta t)$ are the final values of E found in the two previous frames. At the beginning of a run, E_o is found from

$$E_o = M + \left(e - \frac{e^3}{8}\right)\sin M + \frac{1}{2} e^2 \sin 2M + \frac{3}{8} e^3 \sin 3M \quad .$$

The true anomaly v is found from

$$\sin v = \frac{\sqrt{1-e^2}}{1 - e\cos E} \sin E \quad ,$$

with

$$\cos v = \frac{\cos E - e}{1 - e\cos E}$$

helping to decide the quadrant.

The argument of latitude is

$$u = \omega + v \quad ,$$

The radius is

$$\rho = a(1 - e\cos E) \quad .$$

Short period perturbations[31] are now added in:

$$\Delta\Omega = -\frac{A_2}{p^2}\cos i\,[v - M + e\sin v - \frac{1}{2}\sin 2(v+\omega) - \frac{e}{2}\sin(v+2\omega) - \frac{e}{6}\sin(3v+2\omega)] \quad ,$$

$$\Delta i = \frac{1}{4}\frac{A_2}{p^2}\sin 2i\,[\cos 2(v+\omega) + e\cos(v+2\omega) + \frac{e}{3}\cos(3v+2\omega)] \quad ,$$

$$\Delta u = \frac{A_2}{p^2}\left\{(2 - \frac{5}{2}\sin^2 i)(v - M + e\sin v) + (1 - \frac{3}{2}\sin^2 i)\left[\frac{2}{3e}\left(1 - \frac{e^2}{2} - \sqrt{1-e^2}\sin v\right) + \frac{1}{6}\left(1 - \sqrt{1-e^2}\sin 2v\right)\right] - (\frac{1}{2} - \frac{5}{6}\sin^2 i)\, e\sin(v+2\omega) - (\frac{1}{2} - \frac{7}{12}\sin^2 i)\sin 2(v+\omega) - \frac{e}{6}\cos^2 i\sin(3v+2\omega)\right\} \quad ,$$

$$\Delta\rho = \frac{1}{3}\frac{A_2}{p^2}\left[1 - \frac{3}{2}\sin^2 i\right]\left[-1 - \frac{1}{e}\left(1 - \sqrt{1-e^2}\right)\cos v + \frac{\rho}{a}\frac{1}{\sqrt{1-e^2}}\right] + \frac{1}{6}\frac{A_2}{p}\sin^2 i\cos 2(v+\omega) \quad .$$

Then, replace

$$\begin{array}{lll} \Omega & \text{by} & \Omega + \Delta\Omega \quad , \\ i & \text{by} & i + \Delta i \quad , \\ u & \text{by} & u + \Delta u \quad , \\ \rho & \text{by} & \rho + \Delta\rho \quad . \end{array}$$

The right ascension α and declination δ are found from

$$\sin\delta = \sin i \sin u$$

and

$$\cos\alpha \cos\delta = \cos\Omega \cos u - \cos i \sin\Omega \sin u \quad ,$$

$$\sin\alpha \cos\delta = \sin\Omega \cos u + \cos i \cos\Omega \sin u \quad .$$

The program also computes $\dot{\rho}$, $\dot{\delta}$, $\dot{\alpha} \cos\delta$ from

$$\dot{\rho} = \frac{a\,en \sin v}{\sqrt{1 - e^2}} \quad ,$$

$$\dot{\delta} = \frac{\sin i \cos u}{\cos\delta}\, \dot{u} \quad ,$$

and

$$\dot{\alpha} \cos\delta = \cos\delta\ \Omega + \frac{\cos i}{\cos\delta}\, \dot{u} \quad ,$$

where

$$\dot{v} = \frac{na^2 \sqrt{1 - e^2}}{\rho^2} \quad ,$$

and

$$\dot{u} = \dot{\omega} + \dot{v} \quad .$$

Note that $\dot{\Omega} = \Omega_i$ and $\dot{\omega} = \omega_1$ are inputs to the program.

APPENDIX D
CONVERSION FROM GEOCENTRIC TO RADAR COORDINATES

Let r_E be the distance from the geocenter to the radar plane at height h_E above the earth, and d_E the distance from the geocenter to the vertical through the site (Fig. 24), then,

$$r_E = h_E + R_E \cos(\varphi_E - \delta_E) \quad ,$$

and

$$d_E = R_E \sin(\varphi_E - \delta_E) \quad ,$$

where R_E is the earth's equatorial radius, φ_E is the geodetic latitude of the site, and δ_E is the geocentric latitude.

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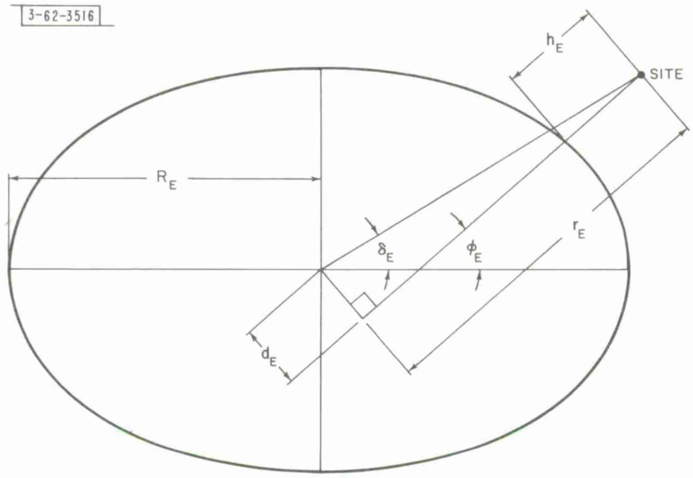

Fig. 24. Figure of earth.

The right ascension of the site Ω_E is found as in Sec. VI-A-4. The satellite is at position ρ, α, δ. The combined effect of rotations and translations is shown in the following equations for the radar Cartesian coordinates of the satellite:

$$x = \rho \cos\delta \sin(\alpha - \Omega_E) \quad ,$$

$$y = \rho\,[\sin\delta \cos\varphi_E - \sin\varphi_E \cos\delta \cos(\alpha - \Omega_E)] + d_E \quad ,$$

$$z = \rho\,[\cos\delta \cos\varphi_E \cos(\alpha - \Omega_E) + \sin\delta \sin\varphi_E] - r_E \quad .$$

Range is

$$R = \sqrt{x^2 + y^2 + z^2} \quad .$$

Azimuth is

$$A = \tan^{-1}\frac{x}{y} \quad .$$

Elevation is

$$E = \sin^{-1} \frac{y}{R} \quad .$$

If R is differentiated with respect to time,

$$\begin{aligned}\dot{R} = \frac{\rho}{2R} \Bigg\{ \bigg[2 + \frac{K_1 \sin\delta}{\rho} - \frac{K_2 \cos\delta \cos(\alpha - \Omega_E)}{\rho} \bigg] \dot{\rho} \\ + [K_1 \cos\delta + K_2 \sin\delta \cos(\alpha - \Omega_E)] \dot{\delta} \\ + K_2 \cos\delta \sin(\alpha - \Omega_E)(\dot{\alpha} - \dot{\Omega}_E) \Bigg\} \quad ,\end{aligned}$$

where

$$K_1 = 2(d_E \cos\varphi_E - r_E \sin\varphi_E) \quad ,$$

$$K_2 = 2(d_E \sin d_E - r_E \cos\varphi_E) \quad ,$$

and

$\dot{\Omega}_E$ is the earth's rotation rate.

ACKNOWLEDGMENTS

Many persons and organizations contributed toward the design and construction of the Haystack computer control system. The drive system and its associated servo system and encoders were provided by the prime antenna contractor, North American Aviation, Inc. The manual modes of antenna control and portions of the console system were implemented at Lincoln Laboratory by A. O. Kuhnel. Many parts of the digital interface equipment were provided under the direction of A. A. Galvin, with the participation of D. R. Bromaghim, W. F. Kelley, and W. H. Drury, and with the contract support of the Computer Control Company. Other important parts of the digital interface system were designed and constructed at Lincoln Laboratory by J. E. Gillis, S. B. Russell, and A. F. Dockery.

The detailed coordination of the program system was arranged by J. D. Drinan, who also constructed several major subprograms. Major programming contributions were made by H. E. Frachtman, R. Teoste, P. Stylos, W. R. Crowther, D. M. Hafford, and S. J. White. Additional programming support was obtained from Adams Associates, Inc.

We would also like to thank H. G. Weiss and J. S. Arthur of Lincoln Laboratory for permitting us the freedom to design and build the computer control system as we saw fit.

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DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None
3. REPORT TITLE Haystack Computer Control System	
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Technical Report	
5. AUTHOR(S) *(Last name, first name, initial)* Heart, Frank E. Mathiasen, Arthur A. Smith, Paul D.	

6. REPORT DATE 27 October 1965	7a. TOTAL NO. OF PAGES 56	7b. NO. OF REFS 32
8a. CONTRACT OR GRANT NO. AF 19(628)-5167 b. PROJECT NO. 649L c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report 406 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TDR-65-497	
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited.		
11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Air Force Systems Command, USAF	

13. ABSTRACT

The 120-foot-diameter Haystack antenna operates at X-band and is used for satellite communications, radio astronomy, and radar astronomy. Haystack will be used to study stars, planets, the sun, the moon, and earth satellites. In order to point this antenna to within 1/10 beamwidth (22 seconds of arc) and to provide flexible control and data processing for diverse users, a digital computer has been tightly integrated into the control system. The parameters of an experiment and computer control are arranged via simple operator discourse through a keyboard/printer. The computer system can simultaneously direct the antenna, process receiver signal data, drive convenient operator displays, and permit operator discourse. Thus, processed signal data may be observed in real time, and modifications to the experiment may be rapidly implemented. The computer control system has been completed and is in full operation.

14. KEY WORDS

Haystack antenna	radio astronomy	Univac 490
X-band	data processing	West Ford
satellite communications	keyboard/printer	signal-to-noise ratio
radar astronomy	man-machine	

Printed by
United States Air Force
L. G. Hanscom Field
Bedford, Massachusetts